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THE UNIVERSITY OF ALBERTA

SURFACE KARST ON GRAND CAYMAN ISLAND, BRITISH WEST INDIES

by

Cheryl Anne Squair

(C)

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

IN

Geology

EDMONTON, ALBERTA

Spring, 1988

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled SURFACE KARST ON GRAND CAYMAN ISLAND, BRITISH WEST INDIES submitted by Cheryl Anne Squair in partial fulfilment of the requirements for the degree of Master of Science in Geology.

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Supervisor

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Date....April 16, 1988.....

DEDICATION

To Lela Goldene Weir, with love.

ABSTRACT

Grand Cayman Island is the type locality of phytokarst. It is essentially flat lying and does not exhibit cone or tower karst that is typical of karst developed in other tropical regions. This is because Grand Cayman Island: (1) is formed predominantly of dolostone; (2) has rapid downward flow of precipitation; and (3) lacks a permanent or ephemeral drainage system.

On Grand Cayman Island surface solution features include root lapies, solution flutes, rainpits, solution cups, grazing cups, cave popcorn, and microfretwork. Larger scale solution forms include grikes, karst wells, irregular pits, pinnacles and caves.

Despite the lack of surface soils over most of the island, the dolostones of the Oligocene-Miocene Bluff Formation support a dense tropical vegetation. Many of the trees and shrubs are rooted directly into the dolostones with the roots penetrating to depths of more than 12 m. These root borings are commonly lined with laminated crusts that are divided into dark and light on the basis of color. The light crusts are formed predominantly of grey and light brown micrites that are extensively bored by fungi. Detrital dolomite, calcite cement and neomorphic calcite spar are minor constituents of the light crusts. Dark crusts are formed of alternating layers of dense opaque filaments and diffuse filaments in brown or dark brown micrite. The outer laminae of dark crusts may contain terra rossa glaebules.

Incorporation of Recent skeletal debris in the laminae of both light and dark crusts and the growth of crusts around roots and rootlets implies that the crusts are Recent.

Crusts are a result of a complex interaction of constructive and destructive processes. Constructive processes include cementation and accretion by incorporation of detrital mineral and organic debris. Destructive processes include etching, replacement (aggrading and degrading) and boring.

Roots and microborers contribute to etching and replacement in the light crusts by producing organic acids and mediating the precipitation of microcrystalline calcite and other organic compounds such as calcium oxalate. The microflora contributes to the growth of the dark crusts by producing micrite as well as by incorporating detrital debris into laminae.

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I wish to thank my advisor, Dr. Brian Jones, for his continued support throughout the duration of this study and especially for that one last chance.

I am grateful to George Braybrook for his assistance and expertise with the Scanning Electron Microscope; to Rob Gardiner for help preparing thin sections; to Bob Young for help with drafting; to Dr. Charles Kahle for his helpful discussions in the field; to Dick Holt, Randy Gallant and Linda Karenko for help preparing the plates; and to my fellow graduate students, especially Dave Liverman, for their encouragement and moral support. Many thanks also to Blair Lockhart for her help and friendship in the field and at home and to Leni Honsaker for her good cheer and willingness to listen. Special thanks to Elaine Andrews, Lori Walton, Karen Kettles, Marc Dubord, Sandra Weir and my brothers, James and Ian for their love and support and a much needed boot now and then.

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I. INTRODUCTION

On Grand Cayman Island in the British West Indies, karst and caliche occur together, with the caliche commonly developing on active karst surfaces. Caliche and caliche formation have been described in detail from localities in Spain, Italy, South Africa, Australia and Florida. Caliche, or calcrete, is typically considered to be a "...fine-grained, chalky to well cemented low magnesian calcite deposit" (Esteban and Klappa, 1983). It is generally considered a semi-arid phenomenon and a useful indicator of subaerial exposure (James, 1972; Harrison, 1977; Esteban and Klappa, 1983). Mechanical weathering accompanied by intense dissolution and/or precipitation are the principal mechanisms of caliche formation and hence the necessity of a semi-arid climate. Karst formation on the other hand, is dependent upon the movement of large volumes of water through a carbonate terrain. Temperature is important for karst development to the extent that karstification proceeds at a much greater rate as temperature increases. Karstification is thus most effective in humid, tropical regions and gives rise to the distinctive landforms of cone and tower karst. Seemingly then, caliche formation should be mutually exclusive from the formation of karst, and indeed, this is the most commonly observed situation. However, in many semi-arid and Mediterranean climates, karst and caliche do occur together with the development of each form taking place at a different time of the year (Harrison, 1977, Esteban and Klappa, 1983). This is so for Grand Cayman Island in the British West Indies.

Grand Cayman Island is also the type locality for phytokarst (Folk *et al.*, 1973) and as such, provides examples of various types of karstification. The most spectacular influence on karst formation is that of the roots of plants on the island.

The presence of roots and their consequent effect on diagenesis in friable, poorly indurated rock or unconsolidated sediments has been extensively documented by workers including Brewer and Sleeman (1963), Carozzi (1967), Glennie and Evamy (1968), Multer and Hoffmeister (1968), Lowry (1969), James (1972), Ward (1973, 1975, 1978), Esteban (1974, 1976), Klappa (1978, 1979, 1980), Semeniuk and Meagher (1981), Cohen (1982), Calvet and Julia (1983), Esteban and Klappa (1983) and Mount and Cohen (1984).

However, the presence of roots in lithified, well indurated rocks has been given only a cursory mention and most of the related references deal with roots in northern, temperate and mountain regions (Stong and La Roi, 1983).

A. Objectives

This study covers three major topics:

1. a. examination of the factors responsible for the karst forms on Grand Cayman Island and hence the reasons for the deviation from typical tropical karst,
   b. how karst formation may be affected by roots and microborers,
2. a. examination of the nature and extent of boring microflora and its effect on weathering,
   b. the relation of boring microflora to root penetration,
3. a. examination of the nature and extent of root penetration and the relation of this penetration to weathering in a modern karst setting,
   b. the effect of root penetration on diagenesis and the resulting textures, with particular reference to creation and destruction of porosity.

The study of a karst environment encompasses both surface forms and speleothemic development. This study deals with the surface forms of the karst environment on Grand Cayman Island and is part of a larger study of the Cayman Islands in general. The speleothemic aspects of karst on Grand Cayman Island were examined by Smith (1987).

B. Methods

Field observations were conducted at High Rock Quarry, Pedro Castle Quarry, Salt Creek, Dolphin Point, Cayman Kai, Bowseland, numerous localities along the Queen's Road and inland footpaths in the eastern part of Grand Cayman Island. Samples were collected from High Rock Quarry, East End, the Queen's Road, Salt Creek and Cayman Kai. All colours were determined using a Munsell colour chart. Unless otherwise stated, colours were determined from dry samples.

Forty-two thin sections were examined. Thirty-eight of these were ground to 30 μm for examination under polarized and fluorescent light. Four were ground to 60 μm and finely polished for reflected light study. All thin sections were impregnated with blue epoxy to enhance porosity. All thin sections were stained with Alizarin Red in dilute HCl to facilitate distinction of calcite from dolomite. Four thin sections known to contain iron were stained with potassium ferricyanide to determine the presence of ferroan carbonates. As no ferroan carbonates were found, the remaining samples were left unstained.

Forty-one samples were prepared for examination with the Scanning Electron Microscope (SEM). Small, fractured samples of rocks and rootlets extracted from the rocks were mounted on aluminum stubs using silver conductive paint. Samples were sputter coated with gold to an approximate thickness of 50 Å. A Cambridge Stereoscan 250 with either a Kevex 7000 Energy Dispersive or a Tracor 5500 Energy Dispersive X-ray Analyzer (EDAX) was used to examine the samples. The EDAX unit permitted chemical analysis of samples in conjunction with morphologic examination.

C. Location and Topography

Grand Cayman Island, the largest of the three Cayman Islands, is situated 300 km south of Cuba and 280 km northwest of Jamaica (Figs. 1, 2). It is the dolostone-capped peak of a submarine mountain, one in the range extending west from the Sierra Maestra of Cuba (Sauer, 1982). It is approximately 35 km long and ranges from 6 to 14 km in width with an area of 197 km^2. Over most of the island, the maximum elevation is approximately 6 m above sea level (Fig. 3); however, at several localities in the north-central part of the island, heights of up to nearly 18 m above sea level are attained. These areas are underlain by dolostones of the Bluff Formation and have well developed karst features (Doran, 1954; Mather, 1972; Folk *et al.* 1973; Bugg and Lloyd, 1976; Stoddart, 1980). The lower lying areas are generally underlain by limestones of the Ironshore Formation (Doran, 1954; Mather, 1972; Folk *et al.* 1973; Bugg and Lloyd, 1976; Stoddart, 1980; Jones *et al.* 1984).

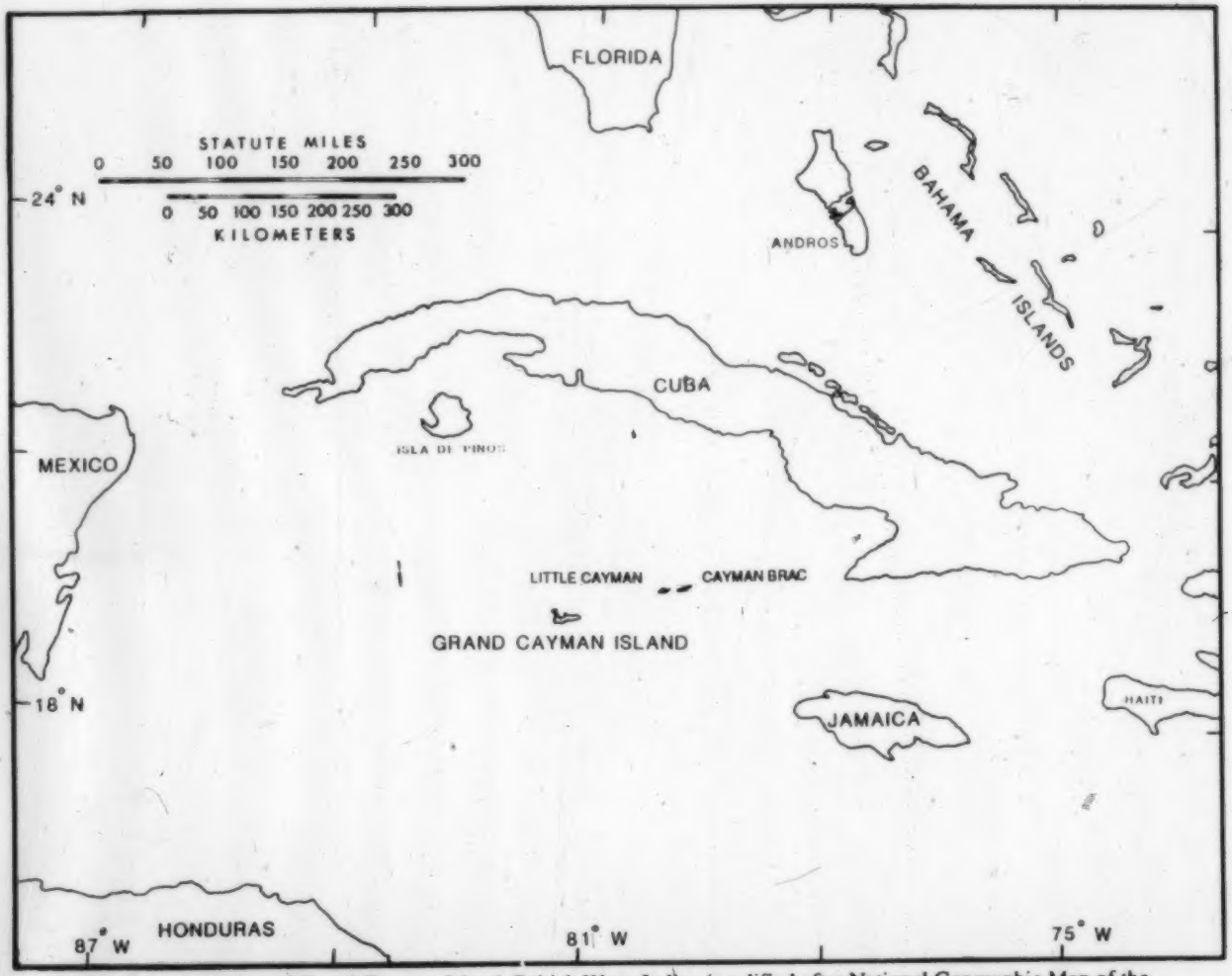

Figure 1. Location of Grand Cayman Island, British West Indies (modified after National Geographic Map of the Caribbean, 1975).

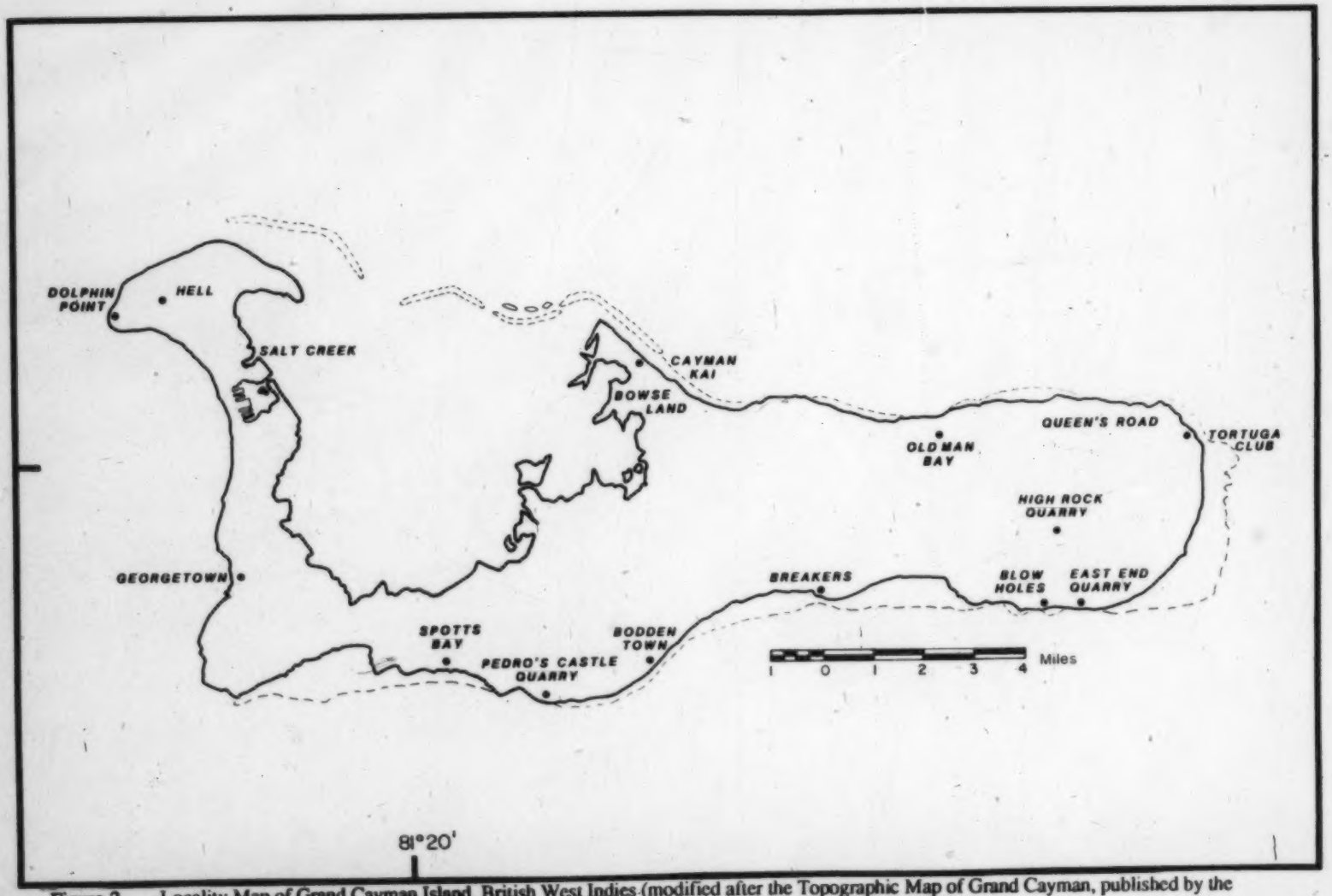

Figure 2. Locality Map of Grand Cayman Island, British West Indies (modified after the Topographic Map of Grand Cayman, published by the British Government's Ministry of Overseas Development (Directorate of Overseas Survey), 1978).

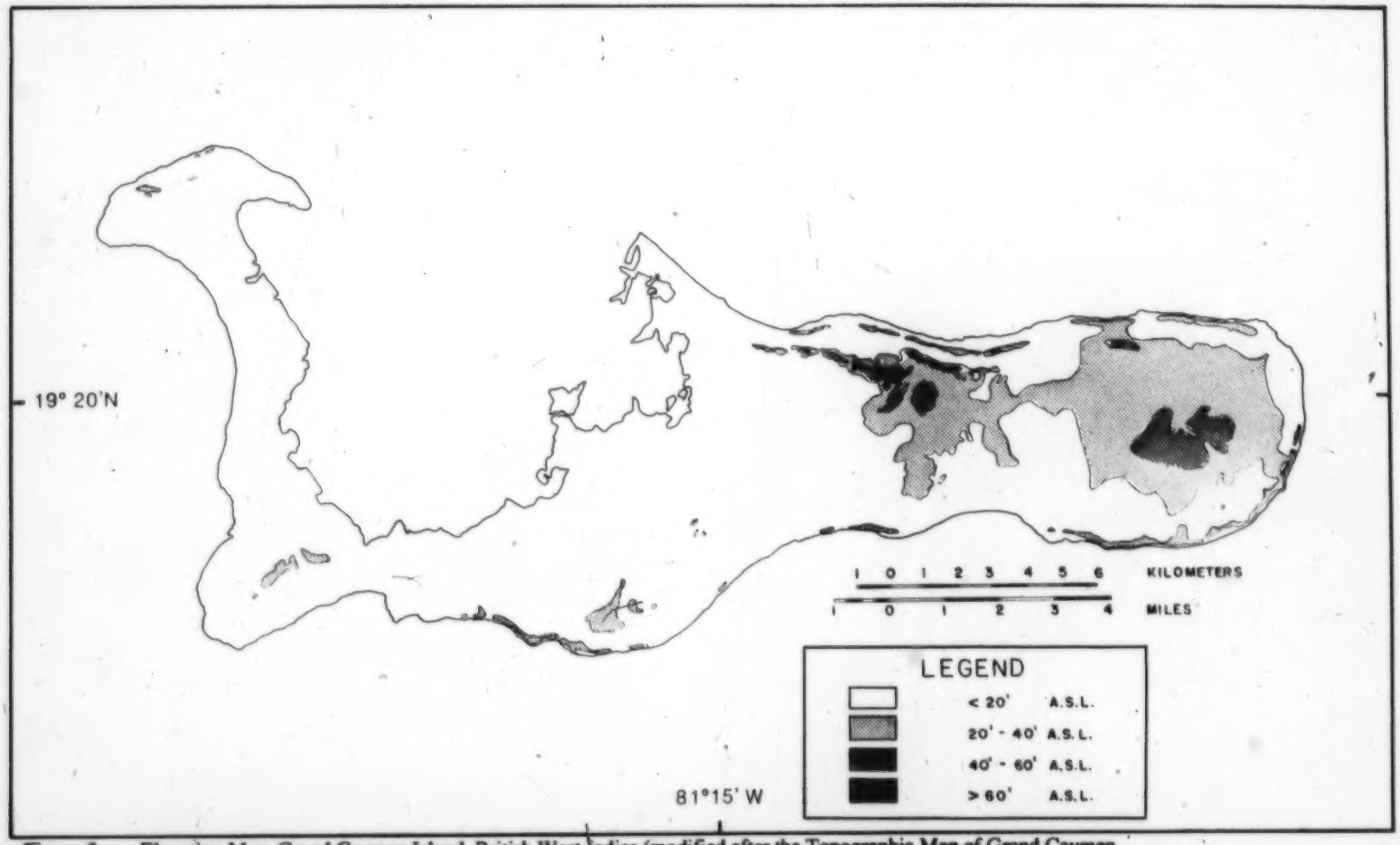

Figure 3. Elevation Map, Grand Cayman Island, British West Indies (modified after the Topographic Map of Grand Cayman Island, published by the British Government's Ministry of Overseas Development (Directorate of Overseas Survey), 1978).

D. Geology

The geology of the Cayman Islands was first described by Matley (1926) and in greater detail by Doran (1954), Richards (1955), Rehder (1962) and Brunt *et al.* (1973). Matley (1926), determined that each of the three islands is composed of a core of Oligocene-Miocene Bluff Formation surrounded by a low-lying fringe of Pleistocene Ironshore Formation (Fig. 4). He determined the ages of the formations using foraminifera, corals and gastropods.

The Bluff Formation consists of intensely dolomitized lagoonal sediments. The formation is not apparently bedded and its thickness has not been determined (Fig. 4). Pleydell (1987) demonstrated that dolomitization was a pervasive event in normal marine to slightly hypersaline waters prior to initial emergence of the island. The dolostone is extremely hard and makes a "chinking" noise when hit with a hammer. Most commonly, the fresh colour is a bright white (N/9), but it is very pale brown (10YR 9/2) in some places. Crystal size ranges from very fine to medium. All aragonitic material has been removed, leaving extremely well preserved molds of gastropods, bivalves and corals. Caymanite, a laminated, multicoloured dolostone occurs as a cavity filling sediment in the Bluff Formation. Lockhart (1986) proposed that pigmentation of the laminae was due to oxidization and precipitation of iron and manganese minerals by bacteria.

The Ironshore Formation consists of poorly indurated very pale brown (10YR 9/2) or pinkish white (5YR 9/2) limestone and it is derived from reefal, lagoonal and beach sediments. It has a soft porous texture, but where it occurs along the shoreline it has commonly been case-hardened (Warthin, 1959; Brunt *et al.*, 1973). On Cayman Brac, case-hardening has been reported to extend as deep as 1.3 m from the surface (K. C. Ng, pers. comm., 1986). Inland, however, calcretes are more commonly developed.

Grand Cayman Island is dissected by a large number of relatively discontinuous joints having orientations of roughly NE-SW and NW-SE (Doran, 1954; Brunt *et al.*, 1973; Emery and Milliman, 1980). Joints in the Bluff Formation were noted to be commonly lined with a soft, porous limestone which strongly resembles the limestone of the Ironshore Formation,

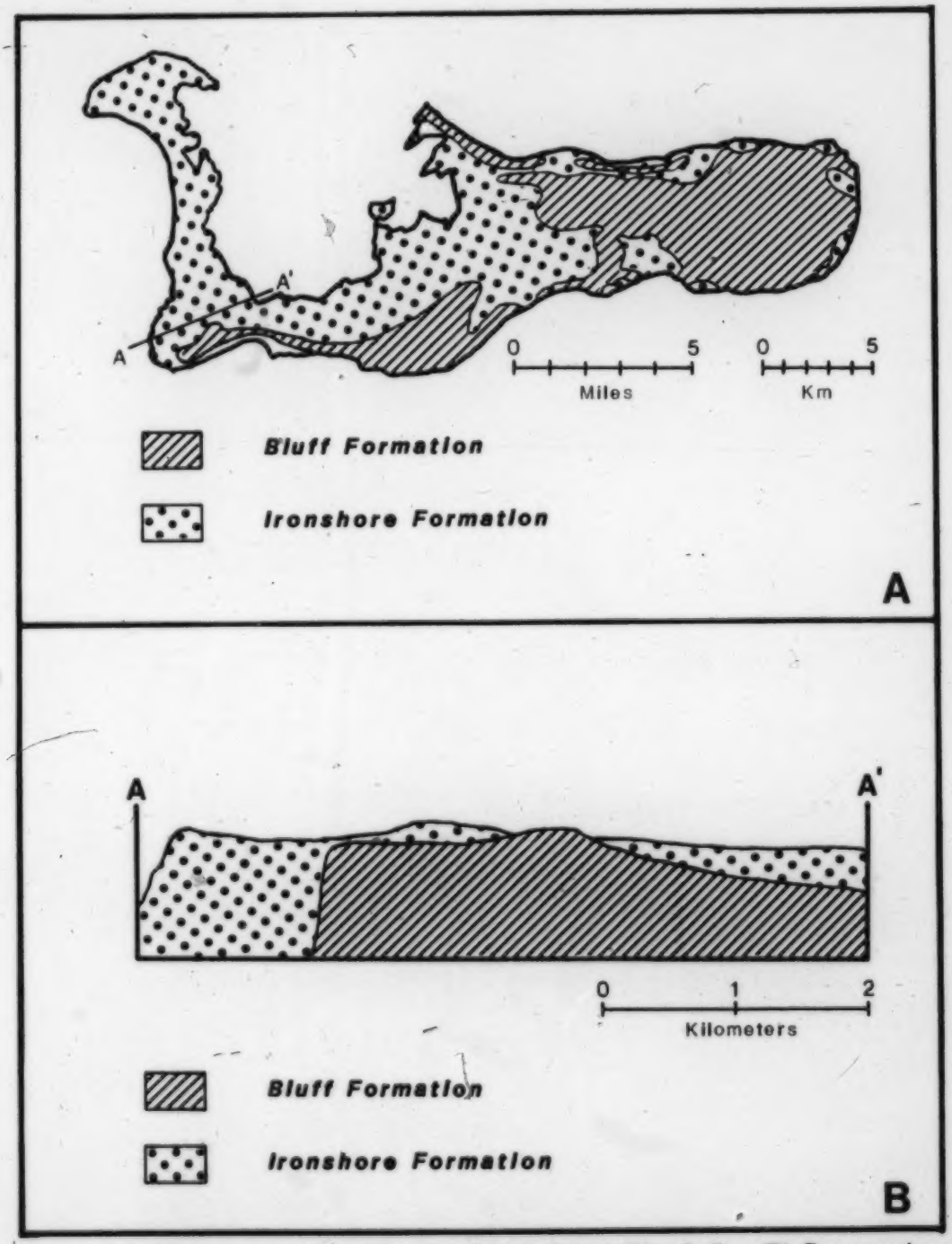

Figure 4. (A) Geology of Grand Cayman Island, British West Indies. (B) Cross-section from A to A' through Grand Cayman Island (modified after Brunt *et al.*, 1973)

but is in fact a weathering product of the Bluff Formation.

There are numerous localities of beachrock on Grand Cayman Island (Moore, 1971, 1973). Beachrock is a result of rapid cementation in the intertidal zone and it is commonly eroded as quickly as it is formed (Jones and Goodbody, 1984b). The beachrock localities on Grand Cayman Island may also be sites of intense biologic weathering (Jones and Goodbody, 1982, 1984b) such as at Boddentown (Fig. 2) where pelecypods, worms, sponge and algae have markedly altered the rock.

E. Climate, Soils, and Vegetation

Owing to the importance of temperature in carbonate dissolution, climate is an important factor in karst development. The formation and distribution of soils and the presence or absence of a forest cover are lesser factors in karst development.

Climate

The major climatic control in the area is the Trade Winds. For most of the year, the winds blow from the ESE, but from December through March, the winds may reverse and come from the northwest. The "Nor'westers", as they are called, are rare storms characterized by high winds and rainfall. The Nor'westers are commonly of 2 to 3 days duration and have the potential to significantly increase the monthly rainfall totals (Stoddart, 1980; Sauer, 1982; M. E. C. Giglioli, pers. comm., 1983).

There are two distinct seasons on Grand Cayman; a wet season (May to October) and a dry season (November to April). The average rainfall in the wet season is 12 to 25 cm/month and in the dry season is usually less than 8 cm/month, with a yearly average of 165 cm (Doran, 1954; Sauer, 1982). The average summer temperature is approximately 28°C and the average winter temperature is approximately 24°C with both seasons having a diurnal temperature range of about 8°C (Sauer, 1982). There is considerable local variation in rainfall on the island. The west side of the island and the southwest corner in particular, from Georgetown south and Pedro west (Fig. 2), receives the greatest amount (190 to 205 cm/yr)

of rain (Sauer, 1982). There is also considerable variation between adjacent stations throughout the island. Variations are thought to be due to patchy convectional rainfall (Sauer, 1982).

Soils

The presence and distribution of soils have a pronounced but lesser affect than climate on karst development. For the purposes of this study, the definition of the Canada Soil Survey Committee (1978, p. 19) is used and states that soil is "...naturally occurring, unconsolidated mineral or organic material at least 10 cm thick that occurs at the earth's surface and is capable of supporting plant growth." For the most part, soil tends to be found in pockets ranging in size from less than 0.2 m diameter and 0.2 m deep to greater than 3 m wide and 1.5 m deep. Where soil forms a continuous layer, it is thin and localized. Soil development in the swampy areas is more extensive and may fill hollows a few square meters to several hectares that vary in depth from 20 cm to greater than 3 m (Proctor, 1984). The poor surface soil development is probably due to the porous and permeable nature of the rocks of both the Bluff and Ironshore Formations. The heavy, frequent rains wash the insoluble residues and organic matter down into cavities, such as sinkholes, or depressions where this matter accumulates and is eventually exposed in pockets. The most extensive soil development occurs on the topographic highs (Fig. 3) of the island - Lower Valley, Savannah, North Ward and the central portion of the East End are the best examples (Proctor, 1984; K. C. Ng, pers. comm., 1986). Several small plantations were located on Grand Cayman Island and Matley (1926) noted that patches of soil several acres in area were cultivated by the residents until the patches were exhausted. The poor quality of the soil and the inhospitable nature of the topography made the plantations money-losing ventures and most of these were eventually abandoned (Sauer, 1982). It is probable that, as a result of clearing the land for the plantations, erosion was considerably accelerated and that much of the soil was lost. This may account for the present day lack of surface soil. Examples of this type of accelerated erosion due to deforestation have been documented in Ireland (Jennings,

1971) and in the tropics (Douglas, 1965).

Doran (1954) noted that plants tend to grow in cavities in the karst where soil has accumulated. However, the vegetation on the island is far denser and widespread than would be possible if plant growth were restricted to the irregularly occurring patches of soil and soil-filled cavities. This may indicate that the initial growth of plants begins in these scattered patches of soil, but with continued growth, vegetation spreads to cover previously barren rock. Modern farming techniques on Grand Cayman Island take advantage of this ability of some plants to root in rock; for example, single lime trees are planted into naturally occurring or man-made patches of soil, while bananas and papayas are grown directly into the rock (K. C. Ng, pers. comm., 1986).

The predominant soil texture is a clay loam; in the uplands, clays are also common and, in the swamps, loams are common. In the uplands, the soils vary in colour from dark brown (7.5 YR 4/4) to dark reddish-brown (2.5 YR 2/4) to dark red (10 R 3/6). In the inland swamps, soil colour varies from dark reddish-brown (5 YR 2/2) to very dark grayish-brown (10 YR 3/2) and mottling may occur. In the marine swamps, the soils are peaty and, where they border the sea, they are saline. They vary in colour from black (10 YR 2/1) to dark yellowish-brown (10 YR 4/4) with dark reddish-brown variants (5 YR 2/2) (Proctor, 1984).

In this study, a dark brown to black pisolitic soil was noted in cavities near the surface (within the top metre) at High Rock Quarry. This soil was commonly associated with decaying root and other organic material. As it was found in no other association, it appears to be a cavity phenomenon.

Vegetation

As a result of intense, but sporadic rainfall, the climate is predominantly tropical savannah with a low vegetation cover. This cover is generally about 6 to 12 m in height, but in some areas a second storey canopy of 18 to 24 m occurs (Proctor, 1984). The height of the canopy is lower than that of similar vegetation in the Caribbean/ Central American region

and this is a result of the poor soil cover on the island (Proctor, 1984). Shrubs, herbs, grasses and sedges predominate along the coastlines and in the cleared areas. On the western side of the island, dense mangrove vegetation (Fig. 5) abounds in the low lying interior areas surrounding North Sound (Doran, 1954; Woodroffe *et al.*, 1980; Woodroffe, 1981, 1982; Sauer, 1982; Proctor, 1984). The interior of the eastern portion of the island is forested by palms, hardwoods, and mangroves in the lower areas, as well as cacti and many sedges, shrubs and herbs (Doran, 1954; Woodroffe *et al.*, 1980; Woodroffe, 1981, 1982; Sauer, 1982; Proctor, 1984).

Occurrence of Vegetation in Relation to Topography and Soil Cover

In general, vegetation on Grand Cayman Island appears dense and abundant. On much of the island however, the dense, impenetrable vegetation that is typical on other tropical islands is not present. In the drier parts of the island, particularly at the east end, the vegetation is not especially dense and there is little understorey vegetation. Foot travel would be easy were it not for the treacherous nature of the phytokarst (Fig. 6, Pls. 2A, 2F). Vegetation in the dry areas tends to form the highest (10-12 m) canopies, however, in the well developed mangrove swamps in the interior of the island, the canopies are also greater than 10 m.

Bare rock is an extremely harsh environment for seedlings to root. However, abundant plant litter accumulates in depressions in the rocks and provides a favorable setting for the growth of seedlings, thereby allowing for the continued growth of vegetation in these areas.

In the wetter, lower portions of the island, dense mangrove swamps occur (compare Figs. 3 and 5). The swamps tend to have a relatively uniform medium (9 m) canopy height. There is some understorey vegetation, but the dense nature of the swamps is predominantly a result of the close-packed nature of the mangrove trees and their abundant prop roots.

In the central portion of the island where the larger patches of soil occur, dense vegetation having a medium height canopy occurs. Trees are closely spaced and dense

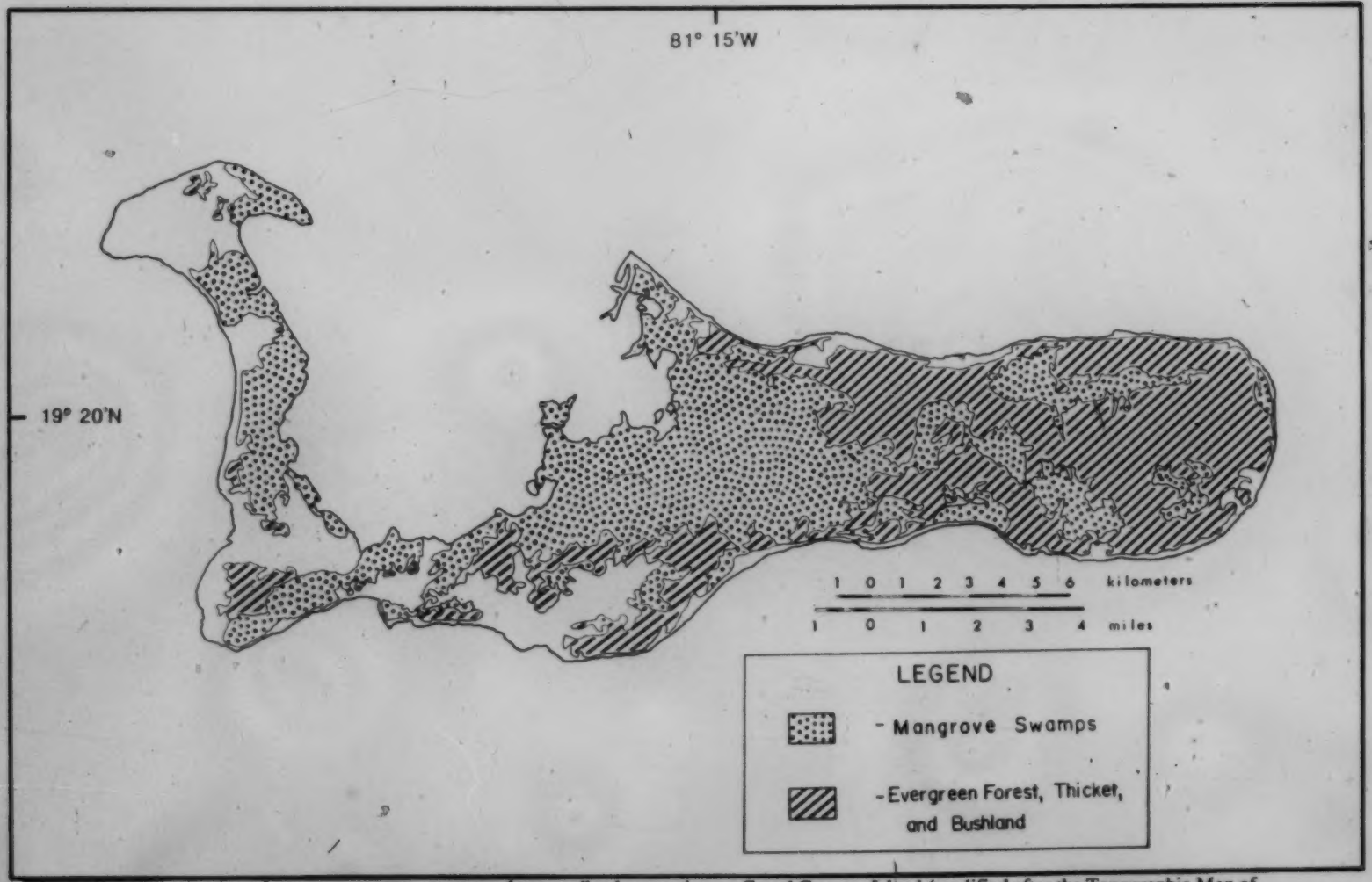

Figure 5. Distribution of mangrove swamps compared to woodland vegetation on Grand Cayman Island (modified after the Topographic Map of Grand Cayman, published by the British Government's Ministry of Overseas Development (Directorate of Overseas Survey), 1978).

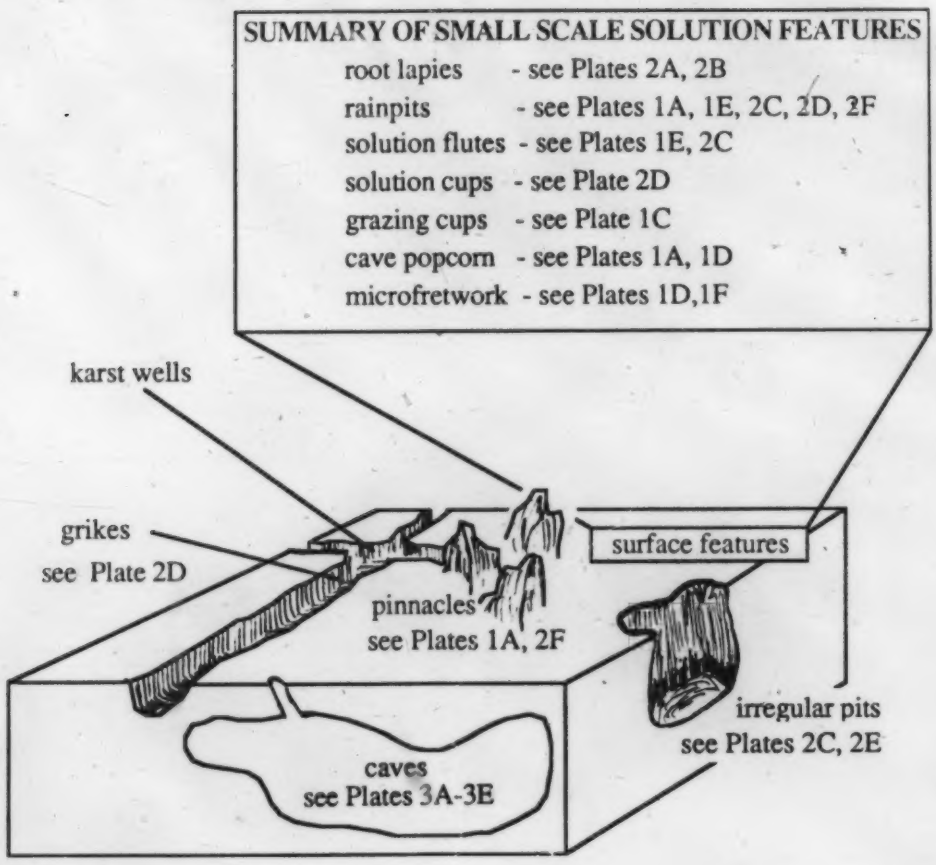
SUMMARY OF SMALL SCALE SOLUTION FEATURES
root lapies - see Plates 2A, 2B
rainpits - see Plates 1A, 1E, 2C, 2D, 2F
solution flutes - see Plates 1E, 2C
solution cups - see Plate 2D
grazing cups - see Plate 1C
cave popcorn - see Plates 1A, 1D
microfretwork - see Plates 1D,1F
karst wells
grikes
see Plate 2D
surface features
pinnacles
see Plates 1A, 2F
irregular pits
see Plates 2C, 2E
caves
see Plates 3A-3E

Figure 6. Summary of solution features on Grand Cayman Island.

understorey vegetation fills any space left among the trees.

Lithology as a Control on Vegetation

The change in the vegetation from one formation to the other is distinct and appears to be controlled by lithology. On the Bluff Formation, the vegetation corresponds predominantly to that of the 'dry evergreen woodland' and to a lesser extent to the 'dry evergreen thicket' described by Proctor (1984). The vegetation is not particularly dense and consists predominantly of trees which include ***Bursera simaruba*** (Red Birch), *Coccothrinax proctorii* (Thatch Palm), ***Ficus aurea*** (wild fig), ***Swietenia mahogoni*** (mahogany) and ***Roystonia regia*** (Royal Palm). There is little vegetation between the trees except for abundant herbs, climbers and succulents (e.g. ***Selenicereus grandiflorus, Philodendron sp., Agave sp.***). In contrast, the vegetation on the Ironshore Formation corresponds to the shrubs of the 'dry evergreen thicket' (Proctor, 1984) and it is extremely dense in nature. Many of the same climbers and succulents are far less abundant than on the Bluff Formation. At the Bowseland locality (Fig. 2), the vegetation on the Ironshore Formation reaches a maximum and uniform height of approximately 3-3.5 m with few or rare emergents. The canopy developed on the Bluff Formation, on the other hand, averages 10-12 m with many taller emergents. The relationship between vegetation and geology may be more complex than has been demonstrated at Bowseland, but if such a relationship could be positively established for the rest of the island, it would provide a useful tool for detailed mapping of the geology.

Effect of Sea Water on Vegetation

In coastal areas, distribution of vegetation corresponds to a fairly consistent pattern that reflects the degree of influence by sea water. Three distinct zones are commonly present (Fig. 7): a wave zone, splash zone and spray zone. In the wave zone, vegetation is sparse if present and characterized by lichens. In the splash zone, vegetation is more abundant, though still sparse, and characterized by lichens and salt-tolerant herbs and succulents such as *Sesuvium* and ***Batis*** (Sauer, 1982; Proctor, 1984). Rare dwarfed shrubs may also be present. In the spray zone, vegetation increases rapidly away form the shoreline. Lichens, herbs and

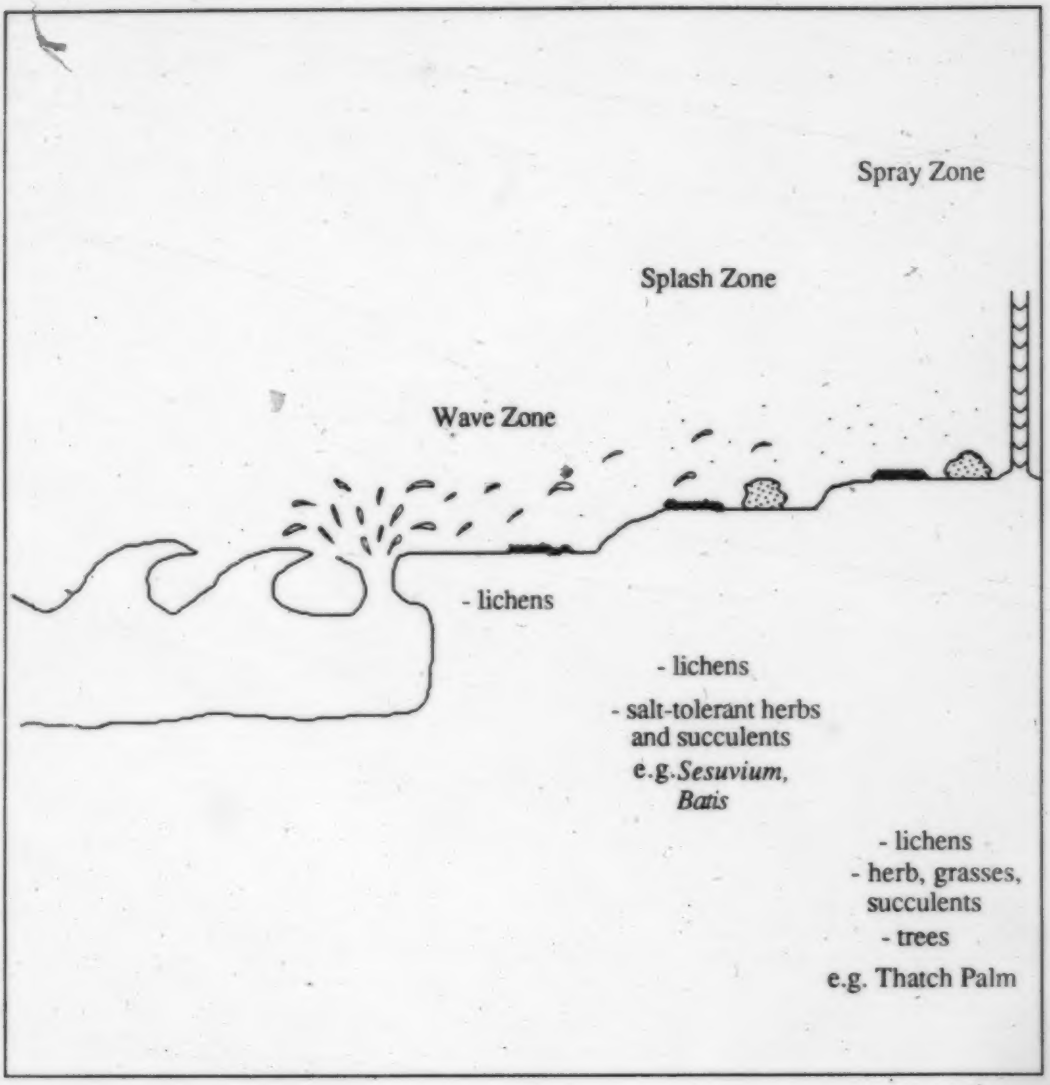

Figure 7. Schematic diagram to show zones developed in response to decreasing amount of sea spray (modified after Schneider, 1976).

succulents grade into shrubs and trees which increase rapidly in number and density.

II. CARBONATE DISSOLUTION: THE PRIMARY EROSIVE AGENT ON GRAND CAYMAN ISLAND

A. Definition of Karst

Karst is a general term used to describe terrains consisting predominantly of highly soluble rocks, such as limestone, dolostone, and evaporites, in which the main agent of erosion is dissolution. These terrains are characterized by a number of distinctive landforms and hydrologic patterns. The word karst is the German derivation of the Slovene term Krs or Kras, the orographic proper name, and the Italian term carso, a general term, for the northwestern region of the Dinarids in Yugoslavia (Jennings, 1971; Sweeting, 1972; Jakucs, 1977; Milanovic, 1981). With time, the term was broadened to a general context to denote limestone terrains exhibiting morphologic features similar to those found in the Dinaric Alps.

Jennings (1971, p. 1) stated that "...karst signifies terrain with distinctive characteristics of relief and drainage arising primarily from a higher degree of rock solubility in natural waters than is found elsewhere." While this definition is generally regarded as adequate, Jakucs (1977) pointed out that this definition ignores other factors involved in karst formation. In many areas, these factors may be equally important as the amount and nature of precipitation and include; (a) the tectonic and diagenetic history of the rock, (b) the volume and/or surface area of the rock available for karstification, (c) the climate, (d) the nature, type, abundance and influence of the local flora, and (e) the presence or absence of a soil cover (Jakucs, 1977). While several of these factors are unrelated in any way, most of the processes involved in karst formation are interdependent and related to the climate operating in the area of interest. Jakucs (1977, p. 17) therefore proposed the following definition:

> "...karst is a stage, with a characteristic appearance, in the development of dominantly mountain-forming rock, together with the natural phenomena associated with it, whose origin and evolution are the complex result of a peculiar petrographic constitution, and an interplay in space and time of various geological, geographical,

climatological and biological causes and environmental conditions."

Karst, as a form, is therefore representative of an instant in time in the evolutionary process of a limestone or similar terrain.

Consequently, both major and minor karst forms change as a karst region evolves. These forms also change if the environment changes. Major shifts in climate produce changes in karst forms and recognition of features that deviate from modern examples can in palaeoclimatic interpretation.

B. Carbonate Dissolution

In tropical carbonate terrains, chemical and mechanical erosion are both important in the development of typical tropical karst features. On Grand Cayman Island, the low topographic relief provides little difference in elevation, a fundamental requirement for the development of streams and rivers. Consequently, no surface streams have developed and mechanical erosion is limited to the minor sheetwash that occurs during ordinary rains and to the intense, but irregular, activity generated in tropical storms and hurricanes. Chemical erosion (i.e. solution) is therefore the dominant process acting on Grand Cayman Island and an understanding of carbonate solution and precipitation is thus essential.

The Carbonate System

The carbonate system is complex and may be affected by a number of factors (Table 1) such as changes in pH, pCO_2, salinity, alkalinity and temperature (Jennings, 1971; Sweeting, 1972; Jakucs, 1977). In pure water, calcite is only moderately soluble, with the values for saturation ranging from 13 to 15 mg/l between 16° and 25°C (Jennings, 1971; Sweeting, 1972). However, its solubility is greatly increased by the addition of carbonic acid to the solute and therefore by an increased partial pressure of CO_2 (Thrailkill, 1968; Jennings, 1971; Sweeting, 1972; Schneider, 1976; Jakucs, 1977; Morel, 1983). Although the $CO_3^{2-} \cdot CO_2 \cdot H_2O$ system can be expressed as a number of simple equations, it is actually a complex series of reversible reactions, each with its own set of equilibria. Each of the different

	FACTORS CAUSING A DECREASE IN CARBONATE DISSOLUTION	FACTORS CAUSING AN INCREASE IN CARBONATE DISSOLUTION
		LOWERING OF pH
		INPUT OF CO_2
	REMOVAL OF CO_2	
	RAISING OF $[Ca^{2+}]$	
SALINITY	INCREASED DISSOCIATION OF H_2CO_3 TO $HCO_3^- + CO_3^{2-}$	
		INCREASED SOLUBILITY PRODUCT OF $CaCO_3$
	DECREASED SOLUBILITY OF CO_2	
T INCREASE	INCREASED DISSOCIATION CONSTANT H_2CO_3 PRODUCES MORE $HCO_3^- + CO_3^{2-}$	
	LOWERING OF THE SOLUBILITY PRODUCT OF $CaCO_3$	
	DECREASED SOLUBILITY OF CO_2	
T DECREASE		DECREASED DISSOCIATION CONSTANT H_2CO_3 PRODUCES LESS $HCO_3^- + CO_3^{2-}$
		INCREASED SOLUBILITY PRODUCT OF $CaCO_3$
		INCREASED SOLUBILITY OF CO_2
P INCREASE		INCREASING DISSOCIATION CONSTANT AND SOLUBILITY OF CO_2
P DECREASE	LOWERING OF DISSOCIATION CONSTANT AND DECREASED SOLUBILITY OF CO_2	
		DECREASING GRAINSIZE OF CARBONATES
	INCREASING GRAINSIZE OF CARBONATES	
	DISSOLVED AND PARTICULATE ORGANIC SUBSTANCES BUILDING COATINGS	
		FORMATION OF ORGANIC AND/OR INORGANIC COMPLEXES
	EVAPORATION OF SOLUTION	
		DILUTION OF SOLUTION

Table 1. Factors affecting carbonate dissolution (modified after Schneider, 1976).

reactions behaves in a particular way when subjected to changing conditions and the sum of these changes results in a change in the system as a whole (Thrailkill, 1968; Jennings, 1971; Sweeting, 1972; Morel, 1983).

Essentially, carbonate dissolution can be described as occurring in four stages, although in fact these stages occur simultaneously (Bögli, 1960). Preceeding the first stage, a small amount of CO_2 from the air is dissolved into rainwater and rapidly reacts to form carbonic acid in its dissociated form of hydrogen and bicarbonate ions:

1. $$CO_2(aq) + H_2O = H_2CO_3 = H^+ + HCO_3^-$$

In the first stage, equation (2), calcite is dissolved through simple physical dissolution:

2. $$CaCO_3 = Ca^{+2} + CO_3^{-2}$$

This stage is rapid and takes approximately 1 second.

The second stage, equation (3) involves the association of the carbonate ions liberated by the dissolution of calcite with the hydrogen ions liberated in dissociation of the carbonic acid:

3. $$H^+ + CO_3^{-2} = HCO_3^-$$

This stage is indistinguishable in time from the first stage, but it nevertheless disturbs the equilibria in equations (1) and (2). Thus, more calcite must be physically dissolved to reestablish equilibrium in equation (2) and stage three is initiated with the transformation of CO_2 into carbonic acid to reestablish the equilibrium between the physically and chemically bound CO_2 in equation (1).

In the third stage, which takes approximately 1 minute, the original CO_2 content in the solution is used in the dissolution of calcite.

The fourth and final stage is the diffusion of CO_2 from the atmosphere into the solution. With the addition of CO_2, the series of reactions begins again and proceeds until a new set of equilibria is established. These equilibria are controlled by the $CaCO_3$ in the solution and the partial pressure of the CO_2 in the atmosphere (Bögli, 1960; Jennings, 1971; Sweeting, 1972; Jakucs, 1977). This situation however, is only true in an open system, where the water is in contact with the atmosphere. In a closed system, water moving through joints

for example, dissolution would stop as soon as equilibrium with the CO_2 dissolved in the solution was established (Sweeting, 1972; Jakucs, 1977). In an open system the most important factor is the rate of diffusion of the carbon dioxide, which is very slow, generally on the order of days (Sweeting, 1972; Jakucs, 1977; Morel, 1983). Temperature also has an effect on the absorption and diffusion rates, but its effect is considerably less than that of the partial pressure of carbon dioxide (Jennings, 1971; Sweeting, 1972; Jakucs, 1977; Morel, 1983). In a groundwater system, the pressure of CO_2 varies from one part of the system to another. The pressure of CO_2 also varies among different soils, and water percolating through these soils tends to equilibrate with its changing surroundings. In situations where the pCO_2 in the water rises, carbonate dissolves and where the pCO_2 drops, carbonate precipitates (Jennings, 1971; Sweeting, 1972; Schneider, 1976; Jakucs, 1977; Morel, 1983).

Under normal surface conditions of pressure and temperature, dolomite is generally considered to be less soluble than calcite (Jennings, 1971; Sweeting, 1972; Rauch and White, 1977). It has been shown, however, that at very high and at very low pressures of carbon dioxide, magnesium is preferentially removed from dolomite (Douglas, 1965; De Groot, 1967). However, at the pressures commonly found in voids and crevices, as opposed to those in soil or rock, magnesium and calcium are removed equally.

Effects of Soil and Vegetation on Carbonate Dissolution

Significant amounts of CO_2 occur in soil and in vegetation litter, produced mainly as a result of root respiration and bacterial and fungal decay of organic debris (Keller and Frederickson, 1952; Jennings, 1971; Sweeting, 1972; Schneider, 1976; Klappa, 1980; Morel, 1983). Any water passing through such material becomes enriched in CO_2 and its aggressivity, or, its ability to dissolve, is thus increased significantly (Garrels and Christ, 1965; Jennings, 1971; Sweeting, 1972; Mason and Moore, 1982; Morel, 1983). Jennings (1971) noted that 20 - 25% CO_2 has been reported from some tropical soils. In addition to the production of CO_2, respiration and decay also produce a large number of organic acids, which may cause dissolution or precipitation of carbonate directly or dissolution through chelation.

The extent to which these acids cause dissolution has however, not yet been demonstrated conclusively (Jennings, 1971; Sweeting, 1972; Schneider, 1976; Krumbein, 1983).

Plants have both a chemical and a physical effect on weathering. Many organic acids, for example pyruvic, citric, oxalic and lactic acids (Kobluk and Kahle, 1978; Krumbein, 1983), are produced by plants. These acids can significantly increase the aggressiveness of groundwaters in one of two ways:

1. the organic acids may themselves dissociate to produce hydrogen ions during hydrolysis; or,
2. many organic acids incorporate Ca^{2+} and/or Mg^{2+} into their structures in the process of chelation.

Plants may also affect chemical weathering by removing Ca^{2+} and other metal ions in direct exchange between root surfaces and mineral surfaces. Roots are commonly in association with an abundance of microflora such as algae and fungi commonly in the form of mycorrhizae (Hatch, 1937; Harley and McCready, 1950; Harley *et al.*, 1953; Harley, 1969; Stark and Spratt, 1977). These microflora also generate organic acids which, like those generated by roots, attack the rock directly, increase the pCO_2 or dissociate to form H^+ ions in groundwater, thereby increasing the aggressiveness of the groundwater.

Plants affect mechanical weathering of rocks in several ways. (1) Growth of the roots into either pre-existing fractures or into cavities formed as a result of etching by root derived organic acids causes fracturing and disintegration. (2) Wherever roots penetrate, have penetrated or have enlarged fractures, conduits exist that permit water to percolate downwards rapidly. This rapid percolation enlarges the conduits further and allows for greater volumes of water to reach great depths. Rapid flow promotes increased dissolution by providing a continuous supply of reactants and by concomitantly removing weathering products (Trudgill, 1985). Rapid percolation also increases mechanical weathering by abrasion. (3) The algae, fungi and bacteria associated with roots also attack the rock directly in the same manner that the roots do, causing fracturing and disintegration on a microscopic scale.

Under typical tropical settings, both types of weathering are greatly affected by the type and nature of the soil cover present. Well developed, permeable soils are important sources of acidity. Respiration of soil organisms, organic decay and root respiration are the major contributors to soil carbon dioxide. Thus, solutions passing through soils have the potential to become highly aggressive and high rates of weathering will take place where the soils are well aerated and flow is constant. Solutions tend to remain in contact with the rock for longer periods of time producing distinct, well rounded features that exhibit smooth, equally etched surfaces.

On Grand Cayman Island, as a result of the lack of a soil cover, chemical and mechanical weathering work in different ways than they do in typical tropical settings. Chemical weathering on Grand Cayman Island is a function of the rapid flow rates associated with sheet wash over bare limestone. In this situation, there are not as many sources of CO_2, but the solutions flowing over the limestone may pick up large amounts of CO_2 from loosely packed organic litter (Trudgill, 1985). While the litter shows only low levels, it produces large quantities of CO_2, especially when wet (Trudgill, 1985). Solution is enhanced when flow is slowed by factors such as low slope angle, rough surface texture or the presence of vegetation. Surface weathering is also a function of porosity and permeability and thus grain size, degree of interlocking and cementation are important factors in the type of surface features developed.

III. KARST DEVELOPMENT ON GRAND CAYMAN ISLAND

A. Description of Tropical Karst

Excluding minor forms, Jennings (1971) and Sweeting (1972) recognized two major types of tropical karst (Table 2): cone karst (or kegelkarst) and tower karst (or turmkarst). Cone karst is characterized by a large number of rounded, roughly conical hills that may be separated by polygonally shaped depressions (Monroe, 1966: Jennings, 1971; Sweeting, 1972). Sweeting (1972) described hills from Jamaica, which varied in height from 100 m to 130 m and up to 1 kilometer in diameter. Cone-karst occurs in Malayasia, the East and West Indies, parts of south-east Asia and in several regions of Central America (Wall and Wilford, 1966; Jennings, 1971; Sweeting, 1972; Jakucs, 1977).

Tower karst is characterized by large, steep (70° - 90°) hills or groups of hills, commonly surrounded by a river or an alluvial plain (Jennings, 1971; Sweeting, 1972). These hills may be 300 m to 400 m in height and form tall, narrow pinnacles or large blocks several square kilometres in area. Tower karst is well developed in parts of Vietnam, China, the Caribbean and Central America (Jennings, 1971; Sweeting, 1972). It is similar in many respects to cone karst and it has been suggested that tower karst is simply cone karst that has developed under special hydrological conditions (Sweeting, 1972). If this is the case, then intermediate forms representing the transition between the two types should be present (Jennings, 1971; Sweeting, 1972), and have, in fact been documented from Jamaica and Puerto Rico (Sweeting, 1972).

Sheetwash and surface runoff are far more common in tropical areas than in temperate regions owing to the extremely intense rainfall. Consequently, torrential streams and rivers tend to form when the rain starts and then virtually disappear when the rain stops. These streams tend to form between limestone blocks and cause intense gullying, which in turn causes formation of limestone islands that eventually form the cones of cone karst (Sweeting, 1972). Sweeting (1972, p. 282) stated that "...tower karst may develop where lateral solution is caused by a temporary or permanent water-level, either in lakes or where

	MORPHOLOGY	SIZE	OCCURRENCE
cone (keglkarst)	rounded, roughly conical hills separatedby polygonal depressions	100-130 m high upto 1 km diameter ~0.75 km^2	Malaysia, East and West Indies and portions of Central America
tower (turmkarst)	large, steep (70° - 90°) hills or groups of hills	300-400 m high ~1.5 m diameter 2-3 km^2 area	Vietnam, China, Caribbean and portions of Central America

Table 2. Comparison of morphology, size and occurrences of cone karst and tower karst . Data derived from Jenning (1971) and Sweeting (1972).

allogenic rivers cross the limestone outcrop and alluviation takes place." Tower karst, however, is also formed without lateral undercutting and alluviation (Sweeting, 1972).

B. Typical Solution Features in Tropical Karst Regions

The development of surface solution features is dependent on a number of factors. The most important of these are the intensity, amount and frequency of rainfall, partial pressure of CO_2 in the rain, or groundwater and the lithology of the rock being dissolved. The surface features that develop on dolostones are essentially the same as those that develop on limestones, but they develop much more slowly and consequently, are subdued and less diverse in comparison to those of the limestones.

There is a vast terminology for karst surface features. Most of the European terminology was collated and standardized by Bögli (1960) in Germany and by Lehmann (1960) in France. For this reason, karst surface features are generally referred to as 'karren' or 'lapiez'. The German terms are awkward to work with and give no information about the form to English-speaking researchers so the terms of Jennings (1971) are used in this study. In view of the large number in present use, terms are reviewed prior to discussing their occurrence on Grand Cayman Island (Tables 3 and 4).

Definition of Small Scale Solution Features

Root Lapies

Holes having roughly circular cross-sections formed by the action of roots occur in the vegetated areas of tropical karst where bedrock is exposed. Schneider (1976) termed these forms root lapies. The diameter of the lapies is isodiametric or non-isodiametric (Bromley, 1970; Golubic *et al.*, 1975; Lukas, 1979). Lapies have diameters that range from 2-10 cm and lengths up to 15 m or more. Lapies shorter than approximately 0.5 m are generally straight with an orientation roughly perpendicular to the ground surface. Lapies longer than 0.5 m may be straight and perpendicular to the ground surface or they may follow tortuous paths of completely random orientation.

FEATURE	OTHER NAMES	DESCRIPTION	SIZE	OCCURRENCE ON GRAND CAYMAN ISLAND
root lapies (Schneider, 1976)		cylinders having roughly circular cross-sections	- 2-10 cm diameter - 0.25 m - >15 m length	found on all rock types wherever there is shrub and/or tree growth e.g. Queen's Road
solution flute (Jennings, 1971)	rillenkarren (Bogli, 1960)	vertical rills, typically semi-circular cross-section and separated by sharp ridges	- 10-15 cm wide - 3-5 cm deep	gravity controlled features - common on steep to vertical (75° - 90°) slopes -rare on gentle slopes (<40°) -most prominent on limestones e.g. Queen's Road
rainpits (Jennings, 1971)		small, roughly hemi-spherical pits	- 0.3-0.5 cm diameter - 0.1-1.0 cm deep	found on slopes of all gradients and on all rock types
solution cups (Zotov, 1941)	solution pans (Jennings, 1971) kamenitzas (Bogli, 1960)	pits with roughly straight sides and a flat bottom	- 5-30 cm diameter - 3-20 cm deep	found on all rock types where trees are the predominant vegetation and there is little undergrowth e.g. eastern interior
grazing cups		solution pits similar to solution cups, but irregular in shape	- 4-12 cm long axis - 2-5 cm deep	common on all rocks of the shoreline e.g. Salt Creek
cave popcorn (Thrailkill, 1965)		aggregates of small, knobbly builds-ups of calcium carbonate closely resembling popped corn	- 2-5 cm long axis of knobbles	found lining insides of caves and cavities and on vertical surfaces of joints and bluffs e.g. East End Quarry
microfretwork		mass of inter-twined thin walled tubes of calcium carbonate having a distinct alveolar texture	-walls <1 mm thick - 1-3 mm diameter	found in close association with cave popcorn e.g. High Rock Quarry

Table 3. Description, size and occurrence of small scale solution features on Grand Cayman Island, British West Indies

FEATURE	OTHER NAMES	DESCRIPTION	SIZE	OCCURRENCE ON GRAND CAYMAN ISLAND
grikes (Jennings, 1971)	**kluftkarren** (Bogli, 1960)	solution widened joints	- 0.2- 1.5 m wide - 1.0-5.0 m deep	common over all the island, but especially noticeable in coastal areas e.g. Blow Holes
karst wells (Jennings, 1971)		vertical cylindrical or conical holes in the rock	- 0.3-2.0 m diameter - 0.5->4.0 m wide	most common along the shoreline, but also occur in the interior portions of the island e.g. Blow Holes
irregular pits		pits, irregular in shape, with relatively straight sides and a flat or slightly concave bottom covered in angular blocks and fragments	- 1.0-10.0 m wide - 1.0-4.0 m deep	occur all over the island, but are best developed in the interior of East End
pinnacles (Folk *et al.*, 1973)	spitzkarren (Bogli, 1960) solution spikes (Jennings, 1971)	slightly conical and rectangular forms which have been strongly etched	- 0.5-2.5 m wide - 1.0-4.5 m high	most commonly developed in interior areas of slightly lower topography than the surrounding area and in association with jointing e.g. Hell
caves		conduits, passageways and cavities of varying shapes and sizes	0.75 m x 0.75 m x 1.5 m to 5 m x 7 m x 12 m	examples known from many localities e.g. Boddentown

Table 4. Description, size and occurrence of large scale solution features on Grand Cayman Island, British West Indies.

Solution Flutes

Vertical rills, called solution flutes by Jennings (1971) are common on most steep (40°) to vertical slopes (80°). As they are a gravity controlled form, they are less commonly developed on slopes with gradients less than 40° (Jennings, 1971; Sweeting, 1972). The solution flutes are typically semi-circular in cross-section and separated by sharp ridges. These features are relatively constant down their lengths. They have widths ranging from 1-12 cm and depths ranging from 1-3 cm. Length is highly variable. Factors such as lithology, gradient and wind direction affect their development and whether other forms such as rainpits are superimposed. Vegetation also effects flute development by disturbing flow patterns and/or by increasing the aggressivity of rainwater due to increased partial pressure of CO_2 after passing over the vegetation. Jones (1966) demonstrated that even minor increases in the pCO_2 over short distances (50 cm) of algae infested rock can increase the aggressivity of the water.

Root Grooves

Another surface form resulting from root action is common on joint surfaces. Root grooves (Wall and Wilford, 1966) are a series of hemi-spherical etchings which cover joint surfaces in a random anastomosing pattern.

Apparently they form as a result of roots penetrating into tight joints and/or cracks at the surface. Acid byproducts of respiration cause dissolution and aid the roots in further penetrating into the rock (Wall and Wilford, 1966).

Rainpits

Rainpits (Jennings, 1971) are small, roughly hemi-spherical pits formed as a result of simple dissolution by rainwater. They are typically less than 3 cm wide and less than 2 cm deep. They are found on all slopes ranging in gradient from horizontal to vertical, and are commonly superimposed on other surface solution features.

Solution Cups

Solution cups (Zotov, 1941) are pits which have roughly straight sides with a flat bottom. They are typically round in shape and vary widely in size. Diameters range from several centimeters to greater than 3 m and depths range from several millimeters to greater than 50 cm (Sweeting, 1971).

Enhanced dissolution is responsible for the form of these cup-like depressions. Organic debris tends to accumulate in depressions or cracks and as this debris decomposes it produces organic acids and compounds which significantly increase the aggressivity of the water falling into the depressions. In the initial stages of their formation, the highly aggressive solution is readily washed out of the depressions. As the depressions get deeper however, the enriched solution tends to remain on the bottom of the depressions underneath the debris. The solutions become even more concentrated as time passes and dissolution in a downwards direction is accelerated, leaving straight sided, flat bottomed depressions (Zotov, 1941).

Grazing Cups

Pits similar to solution cups, but far more irregular in shape are common in littoral zones. These pits typically contain a grazing organism such as a gastropod, echinoderm or chiton. The pits, hereafter termed grazing cups, vary from 4 cm to 12 cm along their long axis and from 2 cm to 5 cm in depth.

The origin of these pits is uncertain. They may be a result of mechanical disintegration brought about by the rasping action of the grazer in its search for food, by dissolution resulting from organic acids secreted by the organism, or by a combination of the two. Owing to the irregularity of this form, grazing cups may be difficult to distinguish from rain pits and solution cups. Noting the proximity of the cups to the waterline will help in modern settings because most of the organisms responsible must live at least below the high tide line.

Cave Popcorn

Cave popcorn (Thrailkill, 1965) is an aggregation of small (long axis 2-5 mm), knobbly deposits of calcium carbonate, which closely resemble popped corn. It has no preferred orientation and is deposited subaerially on cave (cavity) walls, joint surfaces and speleothems by water seeping out from, flowing down from above and /or splashing onto the surface. The main mechanism of formation is deposition of calcite as a result of loss of CO_2 from slowly moving water.

Definition of Large Scale Solution Features

Grikes

The most common large scale solution features are those which form as a result of the vertical drainage of water along planes of weakness. Grikes (Jennings, 1971) are solution-widened joints. They vary widely in size, depending on their environment of formation, but are typically 10 cm to 1 m in width and 0.5 to 5 m in depth. They commonly narrow toward their bases.

Karst Wells

Karst wells (Jennings, 1971) are similar to grikes in that they are a result of the widening of a pre-existing form through dissolution. Karst wells are cylindrical or conical pipes in the rock, typically formed at the intersection of joints. Diameters of these forms vary widely while depths may be up to or greater than 5 m. Many of these pipes result from the widening of holes formed by the passage of roots through the rock. Accumulation of organic debris in these root formed depressions will result in even more rapid dissolution downwards and the eventual formation of a pipe.

Pinnacles

Blocks between some grikes are cut into blocky, rectangular or spiky, conical forms. These forms have an average size of approximately 0.5 m wide and 0.5 m high (Sweeting, 1972) though they may vary widely. These forms may be covered by gravitational karren

such as solution flutes or by non-gravitational fret- and spongework. Folk *et al.* (1973) noted similar forms in which the surface was intricately pitted, with pits intersecting to form sharp edges, giving the blocks a spongy appearance. They termed these blocks pinnacles.

Caves

For practical purposes, caves are defined as cavities large enough for people to enter. For research purposes a better definition is a cavity large enough to allow turbulent flow i.e. a tube with a diameter of approximately 1 cm (Jennings, 1971; Sweeting, 1972; Bloom, 1978). Cave development is structurally or tectonically controlled, but is typically the result of enlargement along a joint or bedding plane. Cave formation is a result of corrasion, corrosion or a combination of the two.

C. Karst Features on Grand Cayman Island

Several features on Grand Cayman Island are not described by Jennings (1971) and names for these features have therefore been taken from other authors where appropriate.

Small Scale Solution Features

Root Lapies

The most abundant surface features are holes and cylinders with roughly circular cross-sections, diameters that range from 2 to 10 cm and average lengths of approximately 25 cm; however, they may extend more than 15 m (Pls. 2A, 2B). Cylinders most commonly end or disappear by changing direction from an essentially horizontal orientation to vertical. Cylinders less than 0.5 m in length typically have their long axes oriented parallel to ground surface, while lapies longer than 0.5 m are straight or follow tortuous paths of apparently random orientation. They commonly contain roots, either living or dead. At both High Rock and Pedro Castle Quarries, cross-sections of these features occur where they intersect a quarry wall. In the interior parts of the island, roots can be traced for many metres over the surface passing through successions of holes and cylinders until they descend vertically. In many of

the holes, a thin laminated crust (5-15 mm) occurs as a lining on the inner surface. These forms are best developed at the East End in the interior forested areas, but they occur on all rock types on all parts of the island. The features are interpreted to be root lapies.

Solution Flutes

Vertical rills, typically semi-circular in cross-section are common on most steep (75°) to vertical slopes (Pls. 1E, 2C). They are less common on slopes less than 75°. The rills are separated by sharp ridges. They are commonly 10 to 15 cm wide and 3 to 5 cm deep.

Depending on the environment in which the rills develop, two end-member forms occur. The inner surfaces vary from smooth to rough with rain pits (0.3 to 0.5 cm wide, 0.1 to 1.0 cm deep) occurring at irregular interval along their lengths. The smoother forms tend to develop on shallower slopes (less than 40 degrees) and examples of this can be seen in the interior at East End (Fig. 2). Pitted forms tend to be developed on steeper slopes (>50°) with good examples of the features occurring on the Queen's Road (Fig. 2). The pitted forms also seem to be more common where the slope is below a canopy of vegetation.

They are especially prominent on the road cuts of the Queen's Road and on the limestones at localities such as Salt Creek (Fig. 2). While these rills are common on the dolostones at the Queen's Road, they tend to be less common on the dolostones on the rest of the island. The rills are interpreted to be solution flutes.

Root Grooves

At a number of localities on the island and particularly evident at Pedro Castle Quarry (Fig. 2) are numerous anastomosing grooves 5 to 20 mm wide and up to 10 mm deep. They occur on exposed joint surfaces. At Pedro Castle Quarry, they extend to depths of 12 m. Many grooves are much longer owing to their anastomosing character. Because they are shallow, the grooves are quickly obscured by other karren such as solution flutes and rainpits after the joint is exposed. These features are interpreted to be root grooves.

Rainpits

On Grand Cayman Island, small hemi-spherical pits occur on all slopes ranging in gradient from horizontal to vertical (Pls. 1A, 1E, 2C, 2D, 2F). The pits vary in diameter from 0.3 to 5.0 cm and in depth from 0.1 to 1.0 cm. They are a common feature on all rock types all over the island and are commonly superimposed on other surface solution features. These pits are interpreted to be rain pits.

Solution Cups

Pits having roughly straight sides and flat bottoms are common in the interior forested areas of Grand Cayman Island. These pits vary in diameter from 5 to 30 cm and in depth from 3 to 20 cm, and also occur less commonly on rocks of the spray zones and increase inland where vegetation is abundant. These pits are interpreted to be solution cups.

Grazing Cups

Irregular pits, commonly containing grazing organisms such as chitons or gastropods, occur on all the rocky shorelines of Grand Cayman Island (Pl. 1C). The pits vary from 4 to 12 cm along their long axis and from 2-5 cm in depth. They are common on all shorelines ranging from the Bluff Formation at Cayman Kai, to the Ironshore Formation at Salt Creek, to the beach rock at Boddentown (Fig. 2). These forms are interpreted to be grazing cups.

Cave Popcorn

Knobbly deposits of calcium carbonate, white (N/9) to buff (7.5 YR 8/3) in colour and resembling popped corn (Pls. 1A, 1D) are common developed on joint and scarp faces. They also line the inside of caves and cavities. The build-ups assume no particular orientation and may be found on the roof, sides or floor. For this reason, these deposits are referred to as popcorn. Popcorn is particularly evident on the road cuts of the Queen's Road (Fig. 2) and in the numerous cavities in the Bluff Formation at High Rock and East End quarries (Fig. 2).

Microfretwork

Microfretwork is a network of open and closed tubules composed of soft, crumbly calcium carbonate (Pls. 1D, 1F), and recognized by its distinct alveolar texture. Walls of the tubules are thin (usually less than 1 mm) with the tubules having diameters of 1 to 3 mm. The tubes appear to be precipitated around living rootlet systems and when the roots die, they leave behind the microfretwork. The mechanism of precipitation is not clear, but it may be a combination of the respiration of the rootlets and their associated microflora and precipitation directly from solution. Microfretwork containing both living and partially decayed roots are however, common. On Grand Cayman Island microfretwork and popcorn commonly develop together. As such, microfretwork is most commonly evident in conjunction with popcorn on the bluffs along the Queen's Road and in cavities in the Bluff Formation, particularly at High Rock Quarry.

Major Solution Features

Very few large scale karst forms have developed on Grand Cayman Island, partly because of the lack of surface flow and partly because of the predominantly dolostone lithology.

Grikes

The most common major solution features are those which form as a result of the vertical drainage of water. Several sets of joints are apparent on Grand Cayman Island and seem to indicate a tectonic control on the roughly triangular shape of the island (Rigby and Roberts, 1978). These joints are typically solution widened and this is especially noticeable in the coastal areas (Pl. 2D), such as Blow Holes. They are 0.2 m to 1.5 m in width and 1.0 to 5.0 in depth. They may however be much larger than this in subaqueous exposures along the coastline. The constant wave action combines both physical and chemical erosion and consequently is more effective at enlarging the joints than the rainwater alone in the interior areas.

Karst Wells

Pipes varying in diameter from approximately 0.3 to 2 m and in depth from 0.5 m to greater than 4 m occur on Grand Cayman Island. They commonly develop at the intersection of grikes and are best seen along the shorelines. A good example of this development occurs at Blowholes on the south coast of the island. They are, however, also common in the interior areas of the island. It appears that many of these pipes result from widening of holes formed by the passage of roots through the rock. Accumulation of organic debris in these depressions will result in even more rapid dissolution, resulting in the formation of narrow pipes. Good examples of this development occur at Bowseland (Fig. 2).

Irregular Pits

In the interior part of the island, large pits are fairly common. These pits are highly irregular in shape, but tend to have relatively straight sides and a relatively flat or slightly concave bottom covered in angular fragments and blocks. They vary in width from 1 m to 10 m and in depth from 1 m to greater than 4 m. Examples occur all over the island with notable ones in the interior portions of the East End (Pls. 2C, 2E). They appear to be best developed in this area because of the greater relief at this end of the island.

The pits are probably the result of more than one mechanism of formation. The large amount of rubble contained at the bottom and their irregular shape suggest that these forms may be the result of the collapse of the roofs of shallow cavities and small caves. Extreme dissolution and dissection or weakening of the roof due to earth movements would allow for accelerated disintegration of the roof and eventual collapse. Closed cavities with roofs dissected to the point that the cavities could be detected were observed in the interior at East End.

Inhomogeneities in the lithology such as permeability, porosity or composition may have resulted in areas with increased dissolution relative to the surrounding areas. These areas of increased dissolution are eventually expressed in the form of irregular pits.

Pinnacles

Present at numerous localities on the island and especially noticeable at Hell (Fig.2) are jagged pinnacles 1 m to 5 m in height (Pls. 1A, 2F). The pinnacles tend to be covered in minor solution features which have been strongly etched. The ridges between the various forms are consequently very sharp, giving the pinnacles a lacy appearance. Some pinnacles are slightly conical in shape, tapering from bases which vary from 0.5 to 2.5 m in width to sharp peaks less than 0.5 m in width. They may also be roughly rectangular. The rectangular forms tend to be somewhat smaller than the conical pinnacles and vary from 1 to 3 m in height and from approximately 0.5 m to 1.5 m in width. Most pinnacles develop in groups in areas that are slightly lower than the surrounding topography with Hell being the best example of this type of development. Pinnacle development is also common in the interior and along the shorelines. Good examples of pinnacle development inland occur near the Tortuga Club, while Cayman Kai displays good examples of shoreline pinnacle development.

A possible explanation for the development of the pinnacles is that they are remnants of intense dissolution on a local scale. In an area with for example, greater porosity, slightly lower elevation, or a different, more soluble lithology than the surrounding area, dissolution would proceed at an increased rate. If for some reason surface drainage was developed and confined to flow down several pipes in the area rather than steady percolation throughout the entire area, dissolution would be fastest down the pipes. Solutional widening would spread from these pipes until they eventually began to coalesce (Fig. 8). At this point the original surface would be gone and a number of residual pinnacles would remain. Hell provides an example of a locality which may have formed in a manner similar to the above scenario. In the interior, pinnacles are commonly bounded by joints. This relationship could provide another mechanism for their development. Dissolution would proceed at a much faster rate along joints than on the surface. Where joint sets intersect each other, blocks of rock would quickly be separated as a result of enhanced dissolution along the joints. With time, roots and microflora would penetrate the blocks and the blocks would assume the features characteristic of pinnacles.

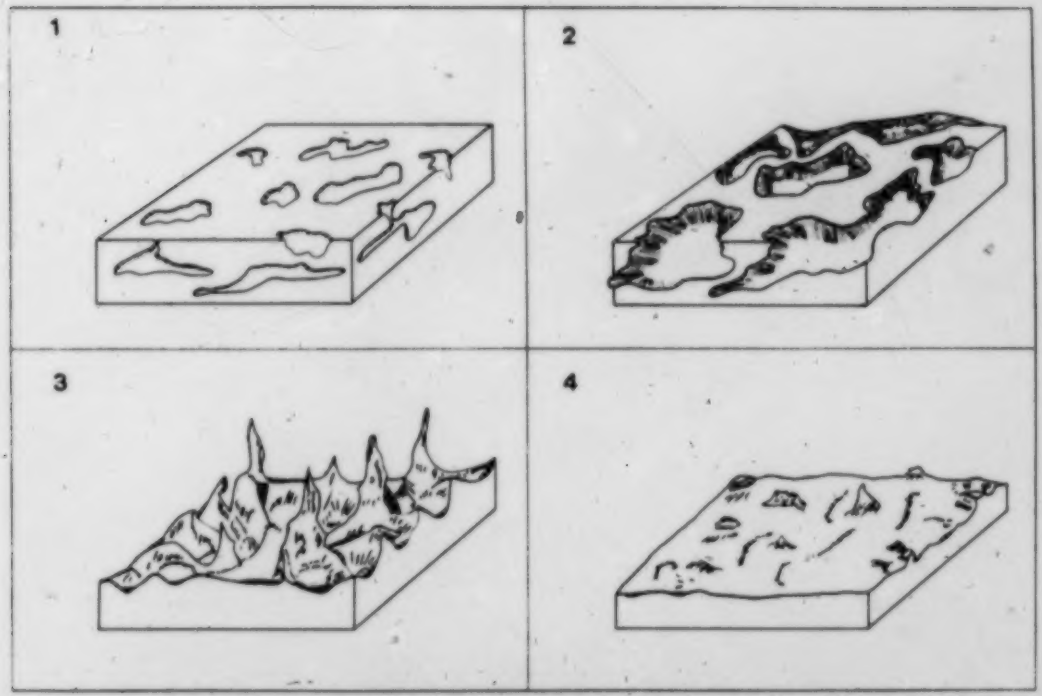

Figure 8. Model for the development of pinnacles at Hell - based on the karst cycle as proposed by Grund (in, Sweeting, 1972). (1) An area of slightly lower topography develops irregular pits and shallow caves at an increased rate relative to the surrounding topography. (2) Pits and caves continue to expand and begin to coalesce. (3) Solution has proceeds to the point where most of the original surface disappears and residual pinnacles remain between pits. (4) Continued solution produces a new surface with small, isolated pinnacles. (Diagram modified after Sweeting, 1972).

Caves

At a number of localities on Grand Cayman Island, for example, Old Man Village and Spotts Bay, large caves occur. Caves vary in size from passageways approximately 0.75 m high, 0.75 m wide and 1.5 m long to chambers approximately 5 m high, 5 to 7 m wide and 10 to 12 m long. Several levels of cave development have been reported by islanders, but only the uppermost level of the caves at Old Man Village were examined by the author.

The caves contain many typical features. Stalactites and stalagmites are abundant (Smith, 1987; Jones and Motyka, 1987; Jones and Smith, in press). The stalactites most commonly occur densely covering the ceiling of medium sized caves (less than 3 m high). The stalagmites most commonly occur in small pockets (less than 1.5 m high). Stalactites are commonly 0.4 to 1.0 m in length, but may grow as long as 2.5 m. Stalagmites are commonly 0.2 to 0.3 m in length, but may be as high as 1.0 m. Rare pillars, combined stalactites and stalagmites, also occur in the caves. (Pl. 3A). In addition to stalactites, stalagmites and pillars, flowstone terraces, cave pearls and drapes are common features in the caves (Pl. 3E). Smith (1987) dealt with these aspects of karst development on Grand Cayman Island in detail.

A striking feature unrelated to normal karst processes is the presence of long tap roots which penetrate the roof of the caves (Pls. 3A-3E) and extend to form a tangled mass on the floor of the caves. The mats are not necessarily formed directly below the roots, rather, once the roots have reached the floor of the cave, they may extend laterally until they reach an area where it appears that water pools during a rain storm. The caves are dry at all other times and are most probably a result of formation at a time when the island was tectonically lower or when the water table was much higher. The roots are important because, in penetrating the rock, they have formed conduits that allow water to drain to great depths. Finely comminuted rock material and organic debris are also moved through these conduits where they accumulate at depth. This material is especially evident in the depressions where the water pools.

D. Deviation of Grand Cayman Island From Typical Tropical Karst

The karst of Grand Cayman Island differs significantly from that in typical tropical karst. This is especially intriguing considering its proximity to the classical examples of tropical karst on Cuba and Jamaica. There is virtually no relief on Grand Cayman Island and the most prominent karst forms developed are the small scale solution features. Similarly, on Cayman Brac, which reaches elevations of approximately 65 m above sea level, cone and tower karst are also missing. This indicates that karst development is not a function of relief.

Monroe (1966) proposed that mechanical erosion in the form of streams and rivers is not an important factor in tropical karst formation, but the lack of tower development on both Grand Cayman Island, which has low topographic relief and on Cayman Brac, which has substantial topographic relief, suggests that abrasion may be an important factor. Of the factors that influence the formation of a karst region, those most responsible for this deviation on Grand Cayman Island appear to be the lithology, the high secondary porosity of the rocks and the combined effect of the limited aerial extent and low relief of the island.

In the areas of classical karst formation, the bedrock lithology is limestone. The most common rock type on Grand Cayman Island is the dolostone of the Bluff Formation. Dolostone weathers at a much slower rate than limestone (Jennings, 1971; Sweeting, 1972; Rauch and White, 1977; Jakucs, 1977; Morel, 1983). Consequently, any tropical karst forms that might potentially develop on the dolostones of Grand Cayman Island would do so at a far slower rate than on the limestones of Cuba and Jamaica. Also, slower developing karst forms would be open to modification by any other active erosional processes, such as boring by microflora, for longer periods of time.

The high secondary porosity and permeability resulting from root lapies, joints, cavities, sinkholes and the dissolution of fossils allow the large volumes of water that are released in tropical storms to drain quickly to great depths. Surface runoff on Grand Cayman Island in the form of streams or rivers is virtually absent for this reason. Impermeable horizons do exist on the island where calcrete crusts or case-hardened layers have formed over areas of the Ironshore Formation. Where these horizons occur on topographic

highs, sheet wash results and the gravitationally oriented karren of normal rainwater solution form; where impermeable horizons occur in depressions, small fresh water ponds will form.

The low relief (maximum 18 m) and small surface area (175 km²) of the island provide a limited catchment area for the collection of surface waters. This prohibits the development of either permanent or ephemeral surface drainage. The consequent lack of streams and rivers provides no permanent or semi-permanent means of mechanical erosion.

The aforementioned factors affecting the lateral solution necessary for the development of tropical/tower karst severely restrict the development of the typical tropical karst cones and towers on Grand Cayman Island. Consequently, in the absence of large scale karst forms, the small scale solution features become extremely well developed and the most striking karst features on the island. The phytokarst described by Folk *et al.* (1973) is a good example of this.

In summary, typical tropical karst features are not developed on Grand Cayman Island owing to the following factors:

1. the dominance of dolostones;
2. the downward flow of precipitation; and
3. lack of a permanent or ephemeral surface drainage system.

E. Summary

While the overall aspect of the karst forms on Grand Cayman Island may vary from those associated with the typical tropical karst found on neighboring Cuba or Jamaica, many typical karst features are present there. Small scale solution features include root lapies, root grooves, rain pits, solution cups, encrustation cups cave popcorn and microfretwork. Large scale solution forms include grikes, solution pipes, collapse pits, pinnacles and caves. The close inter-relationship of karst features with plants makes Grand Cayman Island an ideal location for the study of phytokarst.

IV. PHYTOKARST: A SIGNIFICANT WEATHERING PHENOMENON ON GRAND CAYMAN ISLAND

A. Definition of Phytokarst

Plants play an important role in the weathering process on Grand Cayman Island and are responsible for the formation of features ranging from the microscopic borings of algae and fungi to the lapies and solution pipes formed by roots. In most regions of karst formation, especially in temperate climates, the role played by plants is of secondary or minor importance in the overall karstification process. On Grand Cayman Island, simply owing to the subdued nature or the lack of major karst forms, the ubiquity and dominance of plants in the weathering process are especially conspicuous (Pls. 2A, 2B, 2E, 2F, 3A-3E).

Using Hell (Fig. 2) as the type locality, Folk *et al.* (1973, p. 2351) defined phytokarst as "...a landform produced by rock solution in which boring plant filaments are the main agent of destruction...The process [on Grand Cayman Island] is restricted to attack of endolithic algal filaments...but...can be extended to...other types of endolithic plants, such as fungi." The landforms so produced lack all gravitational orientation and consist of a lacy spongework of "...nested and touching concavities..." (Folk *et al.*, 1973, p. 2354). They further stated that the "...filamentous algae bore their way into limestone to produce black coated pinnacles marked by delicate, lacy dissection..." (Folk *et al.*, 1973, p. 2354).

On a microscopic scale, phytokarst consists of numerous boreholes which penetrate 5 to 10 mm into the surface of the rock in a random fashion (Pl. 4A). The density of the borings is such that the surface area, porosity and permeability, are all significantly increased. The surface of phytokarst is typically black owing to the heavy coating of darkly pigmented algae and also to the presence of decaying organic material in the borings.

B. Validity of the Term Phytokarst

The definition of phytokarst proposed by Folk *et al.* (1973) is extremely specific in both the type of borers that produce it and the landforms produced. However, a dense algal coating occurs on nearly all the rocks of Grand Cayman Island not covered by soil and/or debris cover and, while the spongework texture or the lacy dissection described is common, pinnacle development is not. That microborers are exerting a major influence on the erosion of the pinnacle-free areas, is evidenced by the creation of spongework texture on rocks of both the Bluff and Ironshore formations. Yet, according to the definition *sensu stricto*, the absence of pinnacle development implies that the weathering products in these areas could not be termed phytokarst. Pinnacles on Grand Cayman Island are most commonly developed on dolostone in areas where jointing has occurred, such as at Bowseland (Fig. 2). In addition, pinnacles tend to develop on the Ironshore Formation only where it is in close proximity to the sea and case-hardening has developed, as for example at Dolphin Point (Fig. 2). This would suggest that the presence of microborers is not the primary factor in formation of pinnacles.

Roots also contribute enormously to the overall karstification process by providing conduits that allow water to move quickly through the rocks to great depths. Roots at Pedro Castle Quarry extended to depths in excess of 12 m. Root lapies are abundant over the entire island and contribute to the overall spongy aspect of exposed bedrock.

Use of the Term Phytokarst in this Study

Since all plants clearly play a role in the weathering processes on Grand Cayman Island, it seems appropriate to broaden the use of the term phytokarst to incorporate all landforms whose development has been affected by plants of any kind, both microscopic and macroscopic. Therefore phytokarst will hereafter be used to denote the broadened definition and it is in this sense that it will be throughout the rest of the study. 'Phytokarst' will be used to denote the definition *sensu stricto*.

Biokarst

In most instances, particularly in temperate climates, the role played by plants in the karstification process is of secondary or minor importance. In addition, the surface features produced by grazers and encrusters in littoral karst are commonly covered by a layer of boring microflora. In this case, the boring microflora are contributing to the surface features formed, but the features as a whole are out of the realm of phytokarst, even in the broadest sense. For situations in which many biologic processes are active at once Schneider (1976) proposed the term 'biokarst'. This term has far wider applicability for general geologic use. 'Phytokarst' is appropriate and useful for describing specific environments in a modern setting, but grossly inappropriate for describing ancient rocks in which the small features characteristic of phytokarst are rarely detected. Thus, the term phytokarst is recommended for the description of specific modern settings in which it can be clearly demonstrated that plants predominate in the weathering process and the term biokarst is recommended here for the description of general modern settings and ancient rocks.

C. Variations in Phytokarst on Grand Cayman Island

The character of the phytokarst varies widely depending upon a number of factors, lithology being the most important. In general, the character of the phytokarst falls somewhere between two extremes; that developed on the Bluff Formation and that on the Ironshore Formation. The proximity to the shoreline, the amount and type of vegetation and amount of rainfall will produce local variations of the two end members.

There is a considerable amount of relief developed on the Bluff Formation. This occurs in the form of pinnacles, solution pipes, collapse pits and the generally irregular nature of the spongework. At Hell, for example, pinnacles reach heights up to 2.5 m and irregular pits at East End range up to 2 m in depth. The amount of relief is highly variable depending on the type of features present, with the greatest relief occurring around the solution pipes and joints.

Salt Creek (Fig. 2) provides a good example of the subdued nature of phytokarst on the Ironshore Formation. Except in areas where case-hardening has occurred, forms such as pinnacles and karst wells are absent and there is little local relief. In addition, the entire formation tends to weather to a lower level than the Bluff Formation. This is clearly evident across formation boundaries - the Ironshore Formation occurs as a slight depression surrounded by the higher Bluff Formation as, for example, at Bowseland (Fig. 2) on the north coast. A foot path extends approximately south-west from the road and this path crosses over the Bluff Formation into the Ironshore Formation and back over into the Bluff Formation. The cross-over from formation to formation is marked by a drastic change in the weathering characteristics of the different lithologies of the two formations. The Bluff Formation is characterized by highly weathered joints that result in fissures up to 0.8 m deep and small pinnacles up to 0.5 m high. No soil and little debris has accumulated. Tall trees such as Wild Fig (*Ficus sp.*) and Thatch Palm (*Coccothrinax sp.*) grow directly into the rock (Fig. 9) The Ironshore Formation is characterized by a relatively flat, smooth profile and the accumulation of thin, discontinuous patches of soil. Few tall trees are present and the vegetation is generally more dense.

An example of biokarst occurs along the coastline at Cayman Kai where phytokarst grades into littoral karst. There, the effects of normal rainwater and littoral karst are superimposed on the phytokarst. Algae and lichen are abundant at this locality, especially in the splash zone, which few other plants can survive. The abundance of rooted plants increases dramatically inland from the splash zone. Pinnacle development at Cayman Kai differs from that at Hell where most of the pinnacles are separate entities isolated from each other by as much as 5 m. At Cayman Kai, the exposure maintains a relatively uniform height above mean sea level with pinnacles (Pls. 1A, 2F) developing as a result of deep accentuation of joints and solution pipes. The surface colour is black, even along the waterline, and superimposed on the lacy networked, or spongework, surface are solution cups, grazing cups, solution flutes and other rainwater and seaspray dissolution.

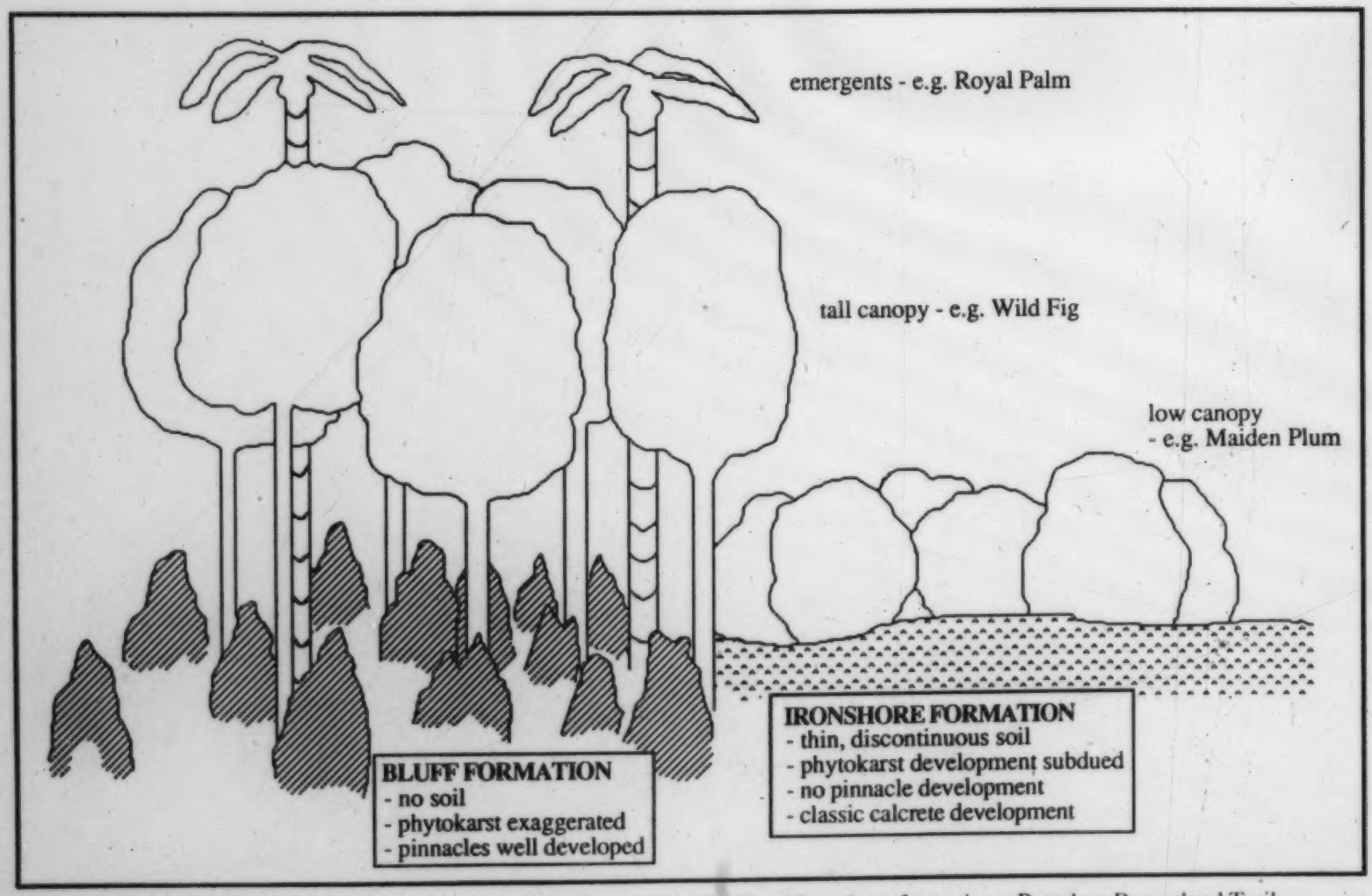

Figure 9. Relationship between vegetation and lithology on the Bluff and Ironshore formations. Based on Bowseland Trail.

D. Salt Creek: An Example of Phytokarst on the Ironshore Formation

The nature of the vegetation found along most of the coastline of Grand Cayman Island is typified at Salt Creek (Fig. 2). Trees, shrubs and vines grow up to the edge of the rocks that occur at the locality. No soil is evident at this locality though organic debris occurs in numerous depressions. Despite this, the vegetation is dense and diverse. The locality is therefore ideal for studying the effects of roots in this particular environment.

Lithology

Jones and Goodbody (1984a) defined three distinct facies in the Ironshore Formation at Salt Creek (Fig. 2). Facies A, the lowermost unit consists of a highly bioturbated oolitic limestone containing abundant *Ophiomorpha* (Fig. 10). Facies B consists of a laminated oolitic limestone that is locally cross-bedded and shows significantly less bioturbation and fewer *Ophiomorpha* than Facies A. Facies C, the uppermost unit, consists of a strongly cross-bedded oolitic limestone showing little bioturbation (Fig. 2). The base of the unit is marked locally by a lag conglomerate having blade-shaped clasts up to 0.5 m long, with their long and intermediate axes oriented parallel to the underlying erosion surface (Figure 10).

The predominant allochems in each of these facies are spherical to ovoid ooids (up to 0.55 mm long) that are characterized by a large nucleus and only 1 or 2 cortical layers (Jones and Goodbody, 1984a). The other allochems, which make up less than 5% of the total, include well preserved fragments of bivalve shells and plates of the codiacean alga *Halimeda*. A small number of these fragments have a well developed micrite envelope.

The nuclei of the ooids consist of dark, dense microcrystalline calcite; Jones and Goodbody (1984a) suggested that they were pellets formed by the burrowing shrimp *Callianassa*. They argued that the ooids formed in quiet-water environments through the activity of bacteria (Jones and Goodbody, 1984a).

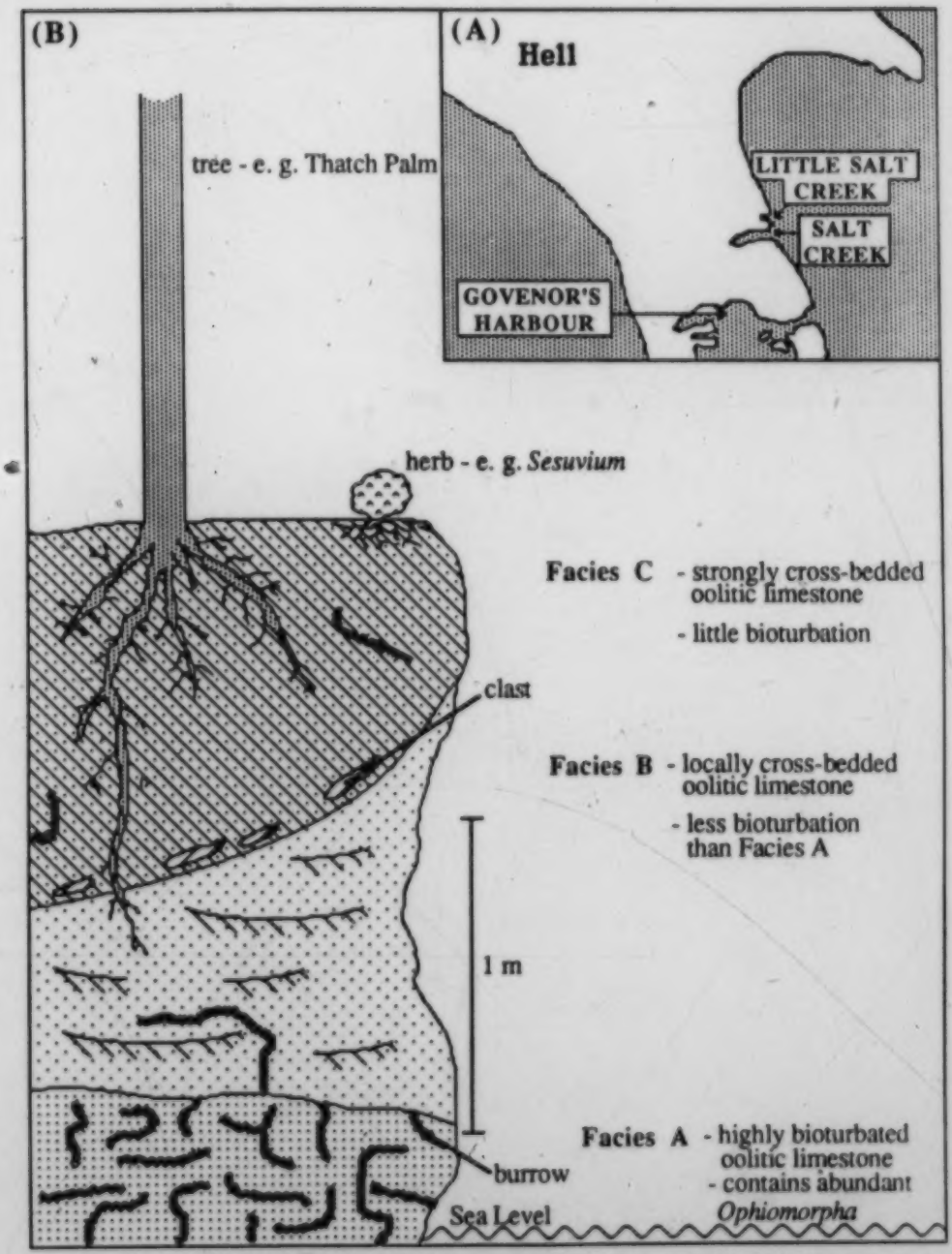

Figure 10. (A) Location of Salt Creek on Grand Cayman Island. (B) Facies present within the Ironshore Formation (modified after Jones and Goodbody, 1984a).

Vegetation

At Salt Creek, there is a distinct lack of vegetation in the zone 6 to 8 m from the shoreline. This zone corresponds to a combined wave/splash/spray zone (Fig. 6) and contains abundant lichen, scattered succulents and rare, dwarfed shrubs. There is no noticeable change in the density or diversity of flora that would correspond with a decrease in salt content, until the 6 to 8 m mark. At this point, the vegetation increases in size and density significantly. A narrow zone (less than 2 m) of varying width, consisting of low (less than 1 m), densely packed shrubs, succulents, herbs and creepers is sharply juxtaposed with a zone of very dense, considerably taller (approximately 4 m) vegetation. This zone consists mainly of mangroves and grades inland to the interior mangrove swamps.

Karst Features

The karst features at Salt Creek are subdued. There is no relief in the form of grikes, solution pipes or pinnacles. The locality is essentially flat, right up to the shoreline, which consists of a small bluff that rises 3 to 3.5 m from the waterline. On the vertical face of the bluffs, encrustation cups, as well as wave and splash produced solution cups are abundant. On the horizontal portion, rain pits are the most common surface form. Wherever an incline is present, solution flutes have formed. The surface colour of the rocks is considerably lighter than the colour at most other localities on the island. The most abundant microborers are lichens and these lichens are not as densely populous or as darkly pigmented as algae and fungi common on Grand Cayman Island.

Borings

A large number of borings penetrate the rocks at Salt Creek. The term boring is herein used to denote any cavity penetrating a hard substrate that has been generated by either chemical or mechanical means (Bromley, 1970; Frey, 1973; Golubic *et al.*, 1975). These borings range in size from 10 μm to greater than 10 cm in diameter and from 20 μm to over 3 meters in length. The macroscopic borings (greater than 20 μm diameter) can most

commonly be attributed to plant roots and rootlets. A number of boring fauna such as bivalves, gastropods, chitons and sponge can also penetrate the rocks near the waterline. The microborings can be attributed predominantly to algae and fungi, however roothairs, bacteria and actinomycetes are also commonly responsible.

Except where the borer is actually present, identification of the organism responsible for producing a particular boring is commonly difficult, if not impossible. The differences between many borings are subtle and easily destroyed by surface weathering. Even the presence of the filament is commonly insufficient for identification of microborers. Many of the physical features of the microboring organisms are similar or overlap. Klappa (1979a) attempted to simplify this problem by compiling a template which compared six main characteristics for the algae, the fungi, roothairs and actinomycetes. The template (Klappa, 1979a, p. 955) is useful in principle, but it is difficult to apply. Many of the diagnostic features used are similar to or mimic those generated by borers in other groups. Other features, such as ramification, require extensive boring development for an accurate determination to be made. Identification of a borer is easier where structures produced by the organism have resisted diagenesis and lithification. The spores and spore producing structures of fungi are an example of this and their presence has been recognized in the rocks of the Bitter Springs Formation which date back to the Precambrian (Schopf, 1970; Schopf and Blacic, 1971).

Examples of borings that occur exclusively in allochems (pre-lithification) and examples of borings which penetrate both allochems and cements (post-lithification) occur at Salt Creek. Many microborings penetrate only the allochems, while a full range from microborings to macroborings penetrate both allochems and cement (Pls. 4B-4D).

The difficulties in distinguishing the many types of microborings and -borers has been a major factor inhibiting the recognition of rootlets and roothairs in the vadose setting. Particularly in samples where the density of borers is high, it is easy to miss subtle differences and to consequently attribute all of the borings to the work of one or two different groups or species. Many types of algae and fungi are not restricted to one particular environment and

are capable of adapting to conditions ranging from light and dry to light-free and phreatic (Jones and Motyka, 1987). Identification of roots therefore becomes very important for providing proof of near surface vadose conditions.

At Salt Creek, roothairs and rootlets penetrate both ooids and cement and they are relatively large (50-100 μm) and are as such easy to identify visually (Pls. 4B-4D). Fungi, bacteria and rarely algae are commonly associated with roots, rootlets and roothairs in a symbiotic relationship (Hatch, 1937; Harley and McCready, 1950; Harley *et al.*, 1953; Harley, 1969; Stark and Spratt, 1977). In this situation, the microflora may help to break down the rock to provide the necessary nutrients or they may simply aid the roots in their penetration of the rock. Consequently, where fungal and algal borings are present on the walls of a larger boring, they support a root generated origin for the larger boring.

Many borings at Salt Creek contain root material, ranging from living roots to collapsed and partially decayed root material. With such material present, the identity of the borers is easy to establish. To identify relationships between these roots and algae and fungi, roots were collected from the spray and splash zones. In a random sampling of 15 roots, 7 contained an abundance of small (approx. 80 μm) mineral bodies on the inner surface of the epidermis (Pls. 4E, 4F, 5A-5D). These bodies varied in shape from nearly spherical to elliptical. Owing to the generally spheroidal nature of the mineral bodies, they are hereafter referred to as 'spheroids'.

Morphology of Spheroids

The spheroids vary in shape from near spherical to elliptical but maintain a uniform size with a maximum diameter (or long axis) of 80 μm. The spheroids randomly cover from 30 to 60% (Pls. 4E, 4F,5A 5C) of the inner surface of the epidermis. However, in some examples, where the inner portion of the root is missing, the spheroids fill the entire volume enclosed by the epidermis where it remains intact (Pl. 4E). Most spheroids appear to be associated with individual cells of the root material (Pl. 5C), but others are distributed randomly and commonly occur in clusters (Pl. 5C). None of the spheroids however, have a

long axis greater than the long axis of the longest cell examined.

The spheroids have no common internal structure. They appear to be composed of blebs or plates of unoriented, cemented mineral matter (Pls. 5B, 5D). Kevex analysis shows that the spheroids have a high Ca content and a very low to negligible Mg content. Small crystals of halite are present on the surface of the spheroids (Pl. 5D) as well as a significant amount of algal, fungal and bacterial matter which penetrates the surface of the spheroids.

Origin of Spheroids

Phytoliths are discrete bodies of silica deposited within the cells, most commonly the epidermal root cells, of grasses and plants (Lutwick, 1969; Birkeland, 1974). The bodies commonly assume the shape of the cell and may be characteristic of the plant in which they are found. Their formation is a mechanism that enables plants to dispose of excess silica absorbed from groundwater, which is used only in trace amounts. In some varieties of plants, the presence of phytoliths also provides mechanical strength to the stems and leaves (Birkeland, 1974). The spheroids resemble phytoliths in that they are formed in the tissue of plants. However, unlike phytoliths, spheroids show no features of either internal or external cell structure.

There are a number of possibilities for the origin of spheroids: (1), as spheroids are a product of one or more of the life processes of the plant (e.g. excretion of excess salts); (2), formed from evaporation of groundwater either during or after the life of the plant; or (3), formed as result of chemical reactions initiated by the liberation of compounds formed during the decay of the plant. Or, for scenario (1), the plant selectively concentrated Ca relative to Mg.

Both calcium and magnesium are essential nutrients of plants (Epstein, 1972) and plants growing into crevices or directly into rock devoid of soil must obtain their nutrients directly from the rock itself and the available groundwater. On Grand Cayman Island, excess calcium obtained in this way may be responsible for the formation of the spheroids in the following manner. Groundwater, high in calcium and magnesium and containing small

amounts of other elements essential to plants such as Na, Mn, Fe and Al is drawn up by the plants at Salt Creek. Excess calcium, and magnesium if there is any, is then excreted by the innermost cells of the epidermis (or possibly the outermost cells of the cortex - Fig. 11) as a calcium mineral such as calcium oxalate, calcium carbonate or other organic Ca compound. They continue to line the epidermis until they are exposed in the decay of the plant.

Significance of Spheroids

The identification and description of the penetration of the rocks by roots are important for several reasons. (1) Most importantly, where the presence of roots can be established as post-lithification, it is unequivocal proof of a near surface vadose environment and thus evidence of immersion. (2) Roots are also actively destroying the limestone and contributing significantly to the karstification process. (3) On a local and microscopic level, roots convert calcium carbonate to a new form. The commonly accepted source of calcium for precipitation of carbonate cements in the vadose zone is from salts contained in seaspray blown inland (James, 1972; Harrison, 1977). If calcium is being recycled from bedrock through the production of spheroids by plants it would support the contention of Jones and Pemberton (1987) that organisms may also contribute calcium for the precipitation of carbonate cements. In addition, the spheroids, representing the calcium carbonate in its new form, may provide ideal nucleation sites for the formation of vadose pisolites and/or digenetic ooids. Root penetration may therefore represent both constructive and destructive phases in a carbonate terrain.

E. Cayman Kai: An Example of Phytokarst on the Bluff Formation

Lithology

The rocks of Cayman Kai (Fig. 2) are all of the Bluff Formation. As at several other localities on the island, the rock is predominantly finely crystalline dolomite. Patches of bright, white microcrystalline dolomite occur irregularly throughout the rock. These patches

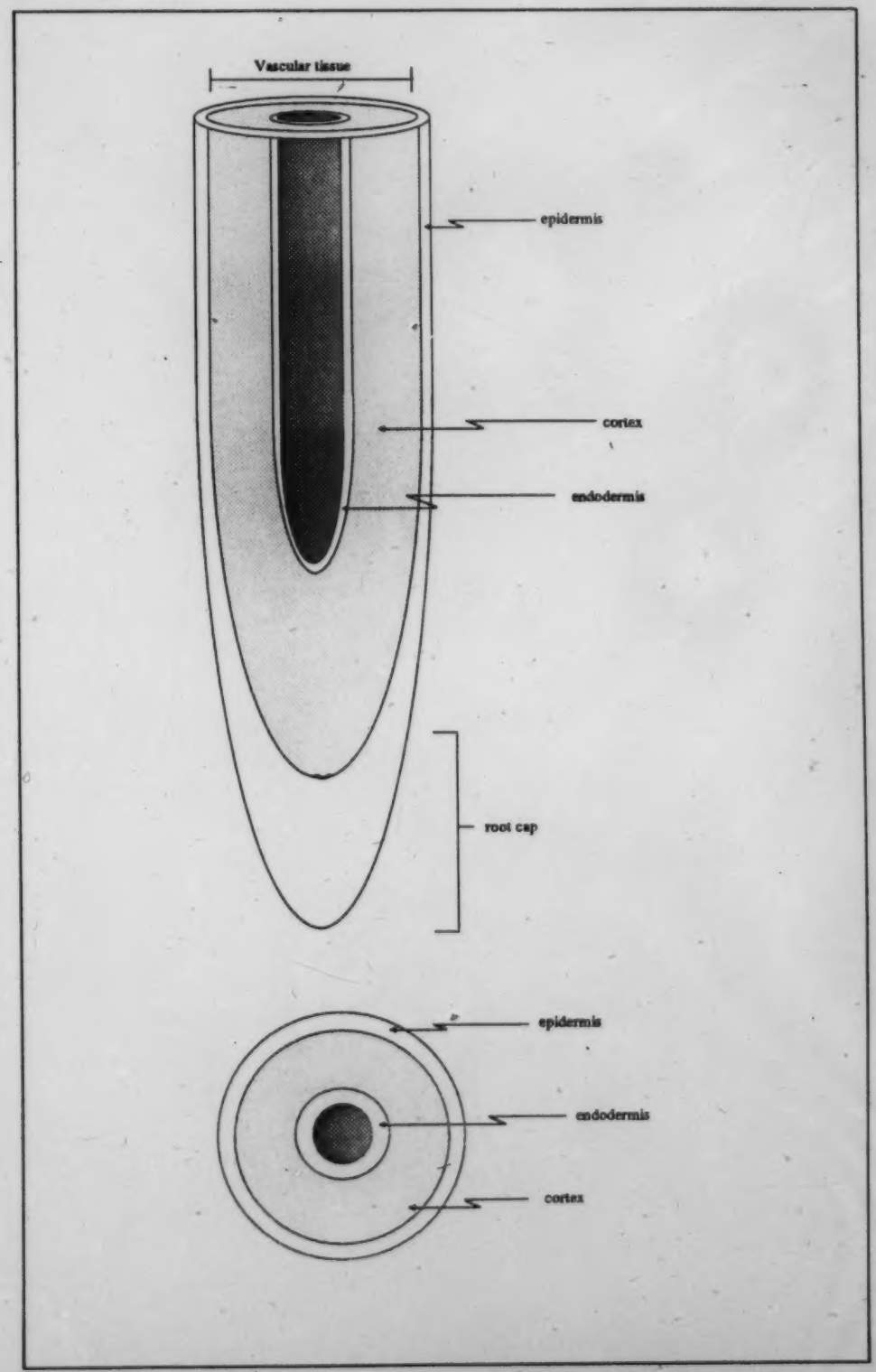

Figure 11. Generalized view of root structure showing position of cortical tissue.

vary from 0.5 cm to 8.0 cm along their longest axis. Though the original sediments of the Bluff Formation were lagoonal, skeletal material has been almost completely leached away, leaving detailed molds that have been filled with micrite. Patches of light-coloured caymanite occur irregularly throughout the outcrop. The fresh, unweathered colour of the rock is a uniform greyish-white, while the surface colour of the rock varies from light grey to dark grey, the lighter colour predominating close to the waterline. The colour darkens where there is a higher concentration of microborers.

Small cliffs 4.5 m in height constitute most of the coastline. The exposure has a relatively uniform height 4 to 5 m above mean sealevel. Slightly higher (5-6 m) and lower (1-2 m) areas result from the accentuation of joints and sinkholes in the karstification process.

Vegetation

Virtually no soil occurs in the area 20 m inland from the shoreline. Beyond this zone, thin patches and pockets of terra rossa occur. Despite this lack of soil, a number of plants occur in this area (Pls. 2A, 2F). Most of the plants are shrubs and herbs that are able to tolerate a wide range of conditions, but many large woody plants such as thatch palms, papaya, maiden plum and buttonwood mangrove also occur. In addition, a number of creepers such as vines and creeping cacti weave in and out of the rocks and in several places form mats covering small areas of the surface. Lichen is abundant.

Three distinct zones of vegetation have formed in this area corresponding to the wave, splash and spray zones (Fig. 6). The wave zone is distinct and varies in width along the waterline from the 5 to 7 m. There is little visible plant growth in this zone except for sparse lichen growth and the rare shrub. The splash zone is approximately 15 m wide. Lichen is abundant in this zone and plant numbers and diversity increase sharply, however, the vegetation remains relatively sparse. This possibly reflects the somewhat lessened, but nevertheless important effects of salt enriched water. Buttonwood, creepers, shrubs and herbs are common in this zone. The boundary between the splash zone and the spray zone is

gradational with the density and diversity of vegetation increasing landward into the nearly impenetrable interior mangrove swamps. The number of large woody plants increases significantly and grasses and sedges also begin to appear.

Surface Karst Features

The rocks of Cayman Kai exhibit a wide variety of karst and seaspray dissolution features. Common karst features include sinkholes, lapies and flutes. Examples of seaspray solution features include flutes and several types of solution pits, similar in many cases to those formed through normal karstification. The type of boring features vary widely according to the borer responsible. Chitons, echinoderms and gastropods form a variety of grazing pits along the waterline. Algae, fungi and lichen produce numerous microborings from the waterline inland and roots of shrubs and trees produce lapies from the splash zone inland.

The weathering character of the rocks in the spray zone is predominantly controlled by the action of seaspray dissolution. Superimposed on this at the waterline are the effects of faunal borers such as chitons and worms. Pits of various sizes and shapes are the dominant features in this zone. Circular depressions 10 to 15 cm in diameter with depths varying from greater than 1 to 4 cm, commonly containing chitons, occur along cliff faces and rarely as far as 0.5 m inland from the cliff edges. Small, elongate tubes 1 to 3 mm in length with widths of approximately 0.5 mm occur in this zone. The tubes increase in number inland and impart a distinctive character to the rocks of Cayman Kai. A great number of other shallow depressions of varying shapes occur in this zone. They vary in width from 0.5 cm to less than 2 cm with highly variable lengths, usually greater than 20 cm, and are probably a result of seaspray and rainwater corrosion.

In the spray zone, the effects of roots become important, while the effects of seaspray dissolution decrease rapidly with increasing distance from the shoreline. Abundant cylindrical holes, many forming networks, characterize the zone. The holes are roughly circular in cross-section and have diameters ranging from 0.2 to 6.0 cm. The diameters are commonly

irregular and usually decrease down the length of the holes. The lengths of the holes are commonly difficult to determine, but they vary from 1 to 8 m and usually end by entering a cavity or network of holes. These holes and networks of holes are commonly associated with plant roots. Other features common in the spray zone include the irregularly shaped depressions, which become abundant in this zone. Features common in the splash zone are the depressions and pits formed by the faunal borers such as chitons and worms.

As a result of the greater number of plants in the spray zone, the surface topography is slightly more exaggerated than in the splash zone. The many root networks evident in this zone have large surface areas and consequently corrosion proceeds at a slightly accelerated rate compared to that in the wave and splash zones. This results in the more prominent highs and lows of the spray zone. These highs and lows vary from approximately 0.3 to 0.6 m compared to the negligible change in the splash and spray zones, *except* where sinkholes and joints are present. Most features present in the splash zone are also present here. The small tubes characteristic of Cayman Kai are also prominent in this zone.

V. DIAGENESIS ASSOCIATED WITH ROOT PENETRATION

The presence of rhizoliths in sediments once soft and friable has been noted by workers such as Glennie and Evamie (1968), Klappa (1980a, 1980b), Semeniuk and Meagher (1981), Mount and Cohen (1984). Penetration by roots into hard, well indurated substrates i.e. root borings, has been largely ignored. Tricart and da Silva (1960), Knox (1977), Harrison and Steinen (1978) and Jones (in press) have, however, noted the presence of root borings associated with caliche development. Roots in these instances appear to have a direct effect on the rocks they penetrate. Deep conduits are commonly produced. The increased porosity and permeability allows for greater chemical and mechanical erosion and the larger volumes of water passing through the rock allow finely comminuted mineral and organic particles to be transported quickly to depth. Roots and their associated microflora also have a direct effect on diagenesis. Cementation, in addition to micritization and replacement, is common.

Grand Cayman Island supports a dense, tropical vegetation, much of which is rooted directly into the bedrock. It is therefore an ideal location for the study of the effect of roots and associated microflora boring into bedrock.

A. Distribution of Laminated Crusts

The most common surface expression of root penetration is root lapies. They are formed by the horizontal and subhorizontal passage of roots along the surface (Pls. 2A, 2B). Root lapies and other root generated karren are most commonly developed on the Bluff Formation. They do however develop on the Ironshore Formation where case-hardening has occurred, such as Dolphin Point (Fig. 2).

The vertical and subvertical expression of root penetration is the development of root borings. The term "bore" is generally used to describe mechanical penetration of a hard substrate. Bromley (1970) and later Frey (1973) and Golubic *et al.* (1975) however, used the term "bore" in reference to organisms, both flora and fauna, in a general sense to describe the penetration of hard substrates by either mechanical or chemical means. Roots penetrating

into indurated bed rock are thus root borings. Jones (in press) used this term in reference to roots pentrating calcrete on Cayman Brac. At Pedro Castle Quarry (Fig. 2), root borings extend at least 12 m from the surface. Many roots were also penetrate the roofs of the caves at Old Man Bay (Pls. 3A-3E). The borings allow finely comminuted particles of mineral and organic matter to be transported to great depths very quickly. This is demonstrated at Old Man Bay caves where pockets of very fine grained sediment have accumulated beneath root formed conduits. Some of the sediment is redistributed by periodic flow of cave-waters and eventually accumulates in depressions where such water has pooled. The sediment is approximately the same colour as surface soil (yellowish red - 5YR 4/6). Roots penetrating into the caves extend to the floors and commonly form intricate interwoven mats in the pockets of sediment.

The root borings are commonly lined with laminated crusts that are up to 2.5 cm thick. These crusts conform to the walls of the borings and extend the length of the conduits. They are abundant at High Rock Quarry, Pedro Castle Quarry and Old Man Bay caves (Fig. 2, Pls. 3A-3E, 6A-6F). These crusts were not generally noted on the surface, however, the extensive black coating of boring microflora would effectively obscure this development.

Description of Crusts

In addition to the laminated crusts that line borings, a number of other crusts occur in association with roots. Crusts commonly line root/soil filled cavities and empty cavities into which roots penetrate (Fig. 12). Crusts range in thickness from 0.3 cm to 2.5 cm. Macroscopically, crusts can be separated into two distinct types on the basis of colour. Light crusts range from light brown to light grey, while dark crusts range from brown and red to black (Pls. 6A-6F). Microscopically, however, differences in colour may be subtle and textural criteria become important. Consequently, at a microscopic level, variations between end-members exist. Thus, macroscopically, crusts will be referred to as light or dark and microscopically they will be referred to as light, dark, or composite.

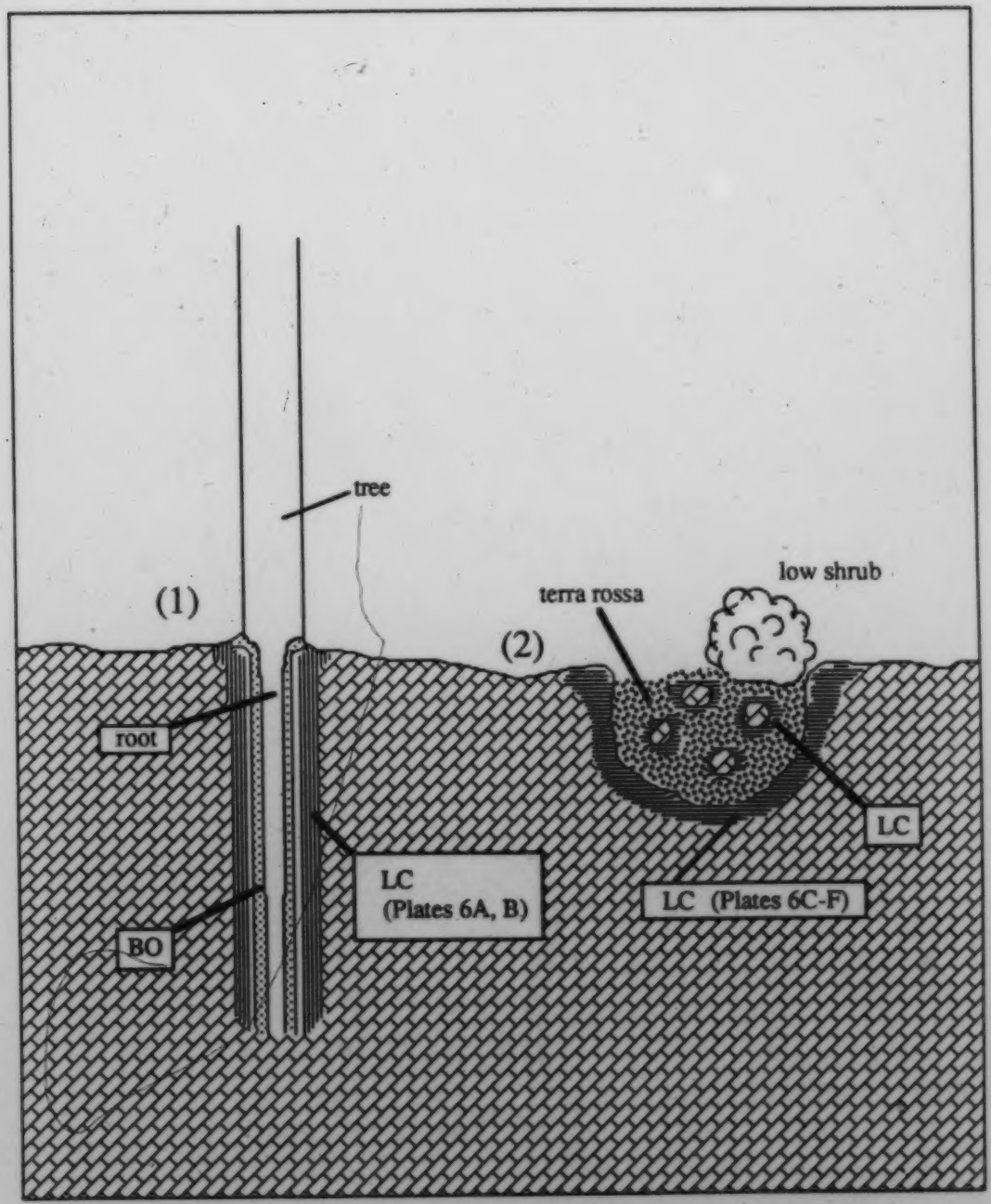

Figure 12. Laminated crust (LC) occurrence on Grand Cayman Island. (1) Laminated crusts line root borings (BO) . (2) Laminated crusts line root and soil filled cavities and outline clasts of Bluff dolostone commonly found in the terra rossa.

Rigby and Roberts (1976) identified three types of calcrete crusts: (1) porous laminated, (2) dense laminated and (3) non-laminated. These crusts are essentially flat-lying and are associated with pedogenic processes. In this sense they may be regarded as classic calcretes such as those described by Blank and Tynes (1965), Multer and Hoffmeister (1968), Reeves (1970) and James (1972). In general, the light crusts identified in this study equate with the dense laminated type, while the dark crusts are similar to the porous laminated type. The greatest similarity between the crusts lining root borings and cavities and those described by Rigby and Roberts (1976) is lamination. Because the field relations of the crust lining root borings and cavities differ greatly from the laminated crusts of Rigby and Roberts (1976), they will be described separately.

Light Crusts

Light crusts (Pls. 6A, 6B), which are densely laminated, range in colour from pinkish grey (7.5YR 7/2) or very pale brown (10YR 8/4) to brownish yellow (10 YR 6/6) or reddish yellow (7.5YR 6/6). Laminae are primarily distinguished on the basis of colour, however textural changes may also contribute to the definition of a lamina. Laminations are parallel or subparallel to the microtopography of the underlying rock; however, laminae commonly thicken to fill in lows, thereby smoothing the outermost surface.

The thickness and regularity of light crusts vary considerably. Crusts conform to the underlying rock as commonly as they do not. Thicknesses vary from less than 1 cm to 5 cm both in crusts and from crust to crust. Where borings have not been filled, the outer surfaces are wavey, bulbous and/or crenulated. Light crusts are also commonly associated with the development of popcorn and microfretwork. In these instances, the innermost laminae conform to the host rock and the outermost laminae are irregular and knobbly. Contacts between light crusts and host rock are usually indistinct.

Laminae are defined on the basis of colour, the presence of stringers of microspar and organic matter, presence of dolomite and bioclastic debris, type and amount of porosity, presence of neomorphic calcite, presence of borers and exhibit wide lateral variation. For example, several distinct laminations defined on the basis of colour may exist in one part of a

crust. Laterally, these colour-defined laminae may merge to become one lamina, thus rendering distintions between laminations impossible. Laminae are commonly separated by discontinuous stringers of microspar and organic matter. Laminae also merge when these disappear. Thicknesses of laminae therefore vary considerably. Where the definition of a lamina is a function of both colour and texture, the thickness of the lamina is relatively constant along its length, though patterns in the laminations may be complex. These patterns may be defined by traces of organic material, stringers of microspar and/or different coloured micrite. Laminae rarely thin over highs and may actually thicken to form knobbles or bulbous structures. Truncations in a set of laminae are rare, however a crust may be comprised of more than one set of laminae with younger laminae pinching out against older laminae.

Light crusts are most commonly associated with root penetration in the absence of soil. This association was particularly evident at High Rock Quarry, where cavities located at varying depths below the surface were well exposed.

Dark Crusts

Dark crusts range in colour from pink (5YR 7/3) or light reddish brown (5YR 6/4) to reddish brown (5YR 5/4) and dark red (10R 3/6). They commonly occur lining the inside of cavities filled or partially filled by soil (Pls. 6C-6F). Cavities containing terra rossa breccia vary widely in size, but are commonly not smaller than 5 cm in diameter. Where cavities are not filled, a red (2.5YR 4/8) to dark red (10YR 3/6), unconsolidated porous layer of terra rossa commonly overlies the dark crust. Many cavities are filled with terra rossa (Pl. 6E).

The crusts also occur in "terra rossa breccias". These are indurated masses of terra rossas that contain angular to subrounded clasts of dolostone from the Bluff Formation. Dark crusts outline the white clasts of dolostone as well as the pockets (Pls. 6E, 6F). Cavities and borings in the terra rossa breccias may also be lined by dark crusts (Pl. 6E).

Initially, the laminae tend to conform to the microtopography of the bedrock or clast. Successive laminae however thicken and thin irregularly, producing wavey outer surfaces.

While thicknesses of individual laminations vary, the overall thickness of any particular crust is relatively uniform. Thicknesses vary from 0.3 cm around clasts to approximately 2.5 cm lining cavities.

Contacts between dark crusts and host rock are usually sharp, but variation does occur. Laminae commonly pinch out along the edge of cavities or around pebbles and cobbles in the breccia. Black laminae may be either continuous or discontinuous along their lengths. The intensity of the colour makes boundaries between laminae very sharp.

B. Petrography

Morphology and Composition of Laminae

Light Crusts

Light crusts are formed predominantly of brown and grey micrites of varying intensities. X-ray analysis (EDAX) associated with Scanning Electron Microscopy indicates that they are relatively pure calcium carbonates containing only trace amounts of iron and magnesium. The calcite spar and microspar that occur as minor constituents are colourless, and are also pure calcium carbonates. At low magnifications, laminae are distinguished on the basis of colour and texture. Textural variations include differences in type (boring, moldic, interparticle/intercrystal, channel/void) and percent (5-30%) of porosity, presence of clastic and bioclastic debris and presence and amount of cement or neomorphic spar. Laminae may also exhibit "clotted textures" which distinguishes them from adjacent laminae. Laminae are commonly separated by parallel stringers of calcite spar and microspar. These stringers are discontinuous and variable in length.

In transmitted light, at medium and high power, variations in colour and textural differences are minimized. The micrite appears much the same from one lamina to another and boundaries become indistinct or disappear. Under fluorescent light however, differences in degree of fluorescence may mark and even accentuate laminae boundaries.

The contact between host rock and initial lamina varies from gradational to sharp. At low magnifications, where micrite is the initial lamination, the contact is sharp. At medium and high magnifications, anhedral to euhedral grains of dolomite (5-7 μm) appear to float in the micrite. These grains are the same size as the dolomite crystals in the alteration zone between the crust and the host rock (Fig. 13a). The situation is similar where calcite spar or microspar forms the initial lamination. Calcite spar and microspore filling pores in the dolostone of host is virtually indistinguishable from the calcite of the lamination. In addition, grains of dolomite float in the calcite of the lamination. Successive laminae are wavey and commonly show complex patterns of thickening and thinning. Bulbous and finger-like forms occur at irregular intervals along the laminae. These forms are generated by the alternation of relatively regular laminae with short crescent shaped laminae. Laminations are rarely truncated by those overlying them, but they may pinch out against a common barrier.

Dark Crusts

In general, dark crusts consist of alternation of two types of laminae. The first consists of clusters of opaque filaments (0.5-1.0 μm diameter, 1.0-2.0 μm long, highly branching). The density of the filaments determines the continuity and thickness of a lamina. Laminae formed of densely packed filaments are relatively uniform in thickness. These laminations commonly grade laterally into micrite that contains fewer filaments. Filaments may grow away from the base, or, both away from the base and into lower laminae. Rarely, filaments penetrate only the lower laminae. These relations also change laterally.

The filamentous structures obvious in transmitted light could not be identified using the SEM and no crystal structure of any kind could be identified for the black laminae in general. X-ray analysis indicates the presence of significant (Ca:Fe approx. 13:1) amounts of iron and manganese in the black laminae. Identification of the opaques was attempted using reflected light microscopy. An exact identification of the mineral(s) composing the filaments could not be made, but colour and reflectance indicate that they may be iron oxides and/or hydroxides. Minor amounts (less than 1%) of hematite and goethite occur in the black laminae. Limonite, identified using transmitted light, may form up to 15% of the black

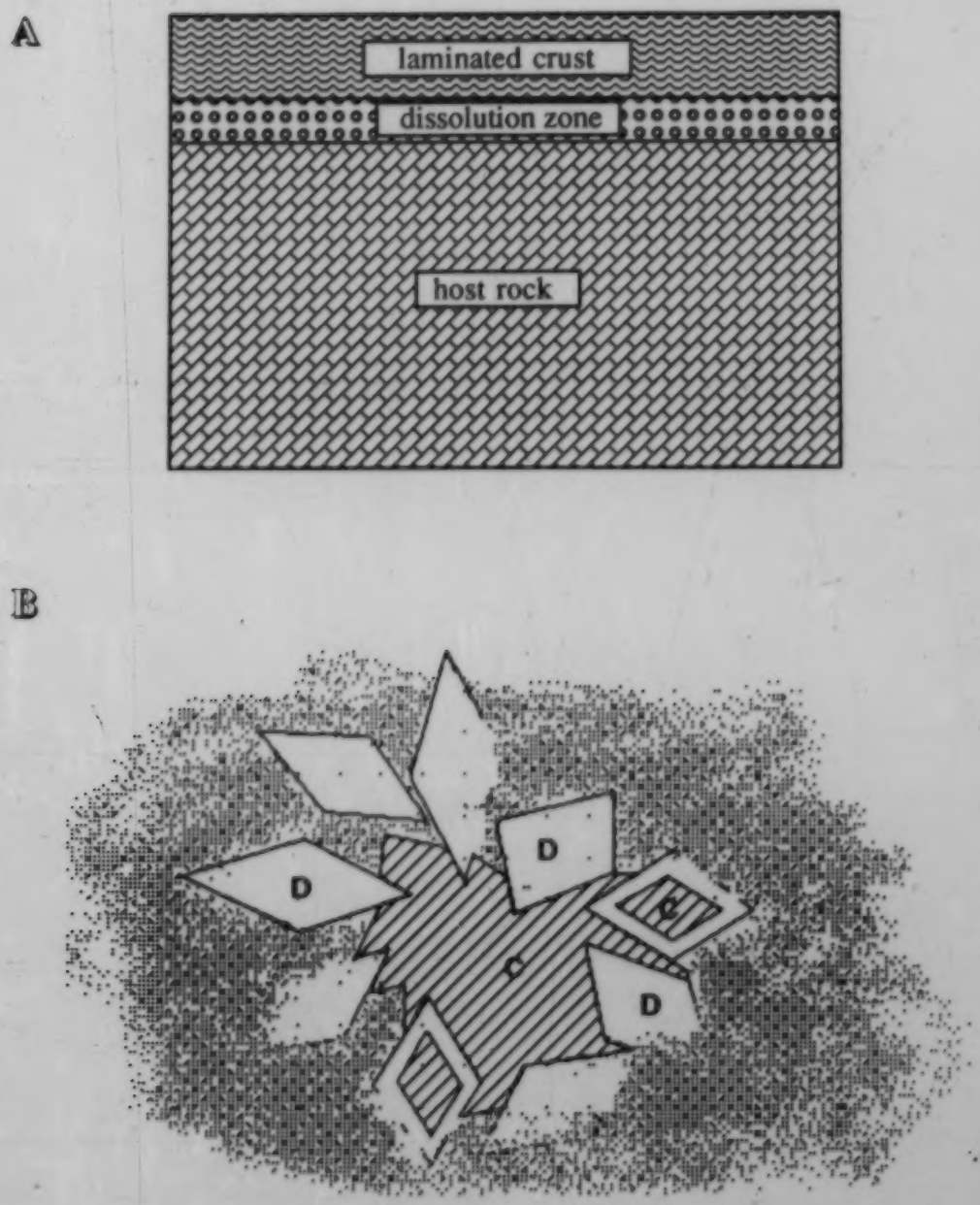

Figure 13 . (A) Cartoon diagram not to scale showing relationship of highly porous zone of dissolution between laminated crust and host rock. Crust contains grains of dolomite similar in size and shape to those that occur in the zone of dissolution. (B) Cartoon diagram not to scale showing well formed dolomite (D) rhombs protruding into a calcite (C) filled cavity. Dolomite rhombs merge into dolomicrite of host rock.

laminae.

The second type of lamination consists of red or brown micrite. The micrite is most commonly structureless but locally contains discrete clusters of the opaque filaments. Irregular patches of iron staining occur and the density of staining determines the intensity of colour of a lamina. Limonite is a common constituent (up to 15%) and the presence of iron was confirmed by X-ray analysis. X-ray analysis also identified aluminum and silicon which indicate the presence of clay minerals. The Si:Al ratio varies from approximately 1.8:1 to 1.2:1. Hand specimens and soil have a "fatty" or argillaceous smell that is characteristic of kaolinite. The high silicon values (Si:Al ratio 1:1 for kaolinite) also indicate the presence of 2:1 clay minerals such as illite or smectites.

The indurated terra rossa consists of glaebules in a matrix of spar or micrite. Glaebules were defined by Brewer (1964) and Brewer and Sleeman (1964) as prolate to equant three dimentional units in the matrix of a soil material, recognizable by their greater concentration of some constituent, their difference in fabric as compared with the enclosing soil material, or by their distinct boundaries with the enclosing soil material. Individual glaebules are classified on the basis of their internal fabric, mineralogy, distinctness as a unit and shape. Fabric types include undifferentiated, concentric, lamellar, continuous and void patterns. Mineralogically, glaebules are accumulations of a particular constituent relative to the enclosing soil material. Usually only a few, commonly only one, of the many constituents present in glaebules has been concentrated (Brewer, 1964; Brewer and Sleeman, 1964). Distinctness as a unit is a function of the sharpness of the external boundary and ease of removal from the enclosing soil material. The shape of glaebules is defined in terms of roundness and sphericity (Brewer, 1964; Brewer and Sleeman, 1964).

The glaebules in the terra rossas from Grand Cayman Island vary widely in shape from roughly spherical to irregular and range in size from 0.25 to 2.0 mm long axis. They are undifferentiated and their boundaries are typically sharp. They appear to consist predominantly of iron oxides and hydroxides, but the dark colour of the iron minerals masks the presence of micrite and clay minerals, which may also be important. Clasts of dolostone,

Recent gastropod and bivalve fragments, dolomite, calcite, limonite, goethite and/or hematite are common constituents of the glaebules.

Composite Crusts

In many instances, dark crusts will contain elements of light crusts and vice-versa. For dark crusts, the position of the light laminae in the crust depends on the type of crust. Where the crust is exposed to the surface, light laminae occur as the outermost layers and where the crust is cylindrical, light laminae commonly occur as the innermost laminations. For light crusts, clusters of the darkly pigmented filaments composing the black laminae may occur as discrete bodies in a lamina or may be densely packed and form distinct layers between light laminae.

Origin of Colour

The colour of laminae in light crusts is probably a result of numerous factors. Organics and other impurities incorporated into the micrites will impart a dark colour. Inclusion of particulate matter and fluid will also impart a dark colour. Changing conditions of formation will affect colour in successive laminae.

The red/brown colour of laminae in dark crusts is predominantly a function of iron staining. Reflected light microscopy indicates that the iron is in the form of goethite and related iron hydroxides. Dolomicrite is dark grey and its colour is probably a function of the factors that produce the colour of yellow and brown micrites.

Intensity of colour may be a reflection of a higher or lower percentage of colourless or lightly pigmented constituent than an adjacent laminae. Higher or lower porosity will have the same effect.

Dolomite Occurrence

Grains of dolomite ranging in size from 2-5 μm are a common constituent of laminae. In light crusts, they are most abundant (up to 20%) in laminae close to the host rock. The percentage decreases in successive laminae away from the host rock. In dark crusts, occurrence and percentage are highly variable, but dolomite grains may form up to 50% of the

matrix. Dolomite grains, rhombic crystals and crystal fragments commonly have highly corroded edges. In many instances, dedolomite with well defined rims of dolomite and cores of calcite spar or micrite remain.

Dolomite also occurs as minor cement (less than 5%) in the cavities surrounding glaebules. It commonly alternates with calcite cement and rarely, it occludes cavities.

Bioclastic Debris

Shell debris is a common but minor constituent of both dark and light crusts. It usually forms less than 5% of the crust. Rarely, fragments may form up to 20% of the crust. The fragments are 0.2 to 5.5 mm long. They occur in glaebules, in the matrix of laminae and cutting across laminae boundaries. In the latter setting, laminae are not distorted around the fragment. Shell debris is predominantly Recent in age and is derived predominantly from gastropods and bivalves. Living gastropods and bivalves occur in the soils associated with crusts and it has been assumed that these are the source of the shell debris. Fossil fragments form less than 1% of organic debris. Red algae is the most common fossil debris. Rare, highly recrystallized shell, gastropod or bivalve, fragments, echinoderm spines and forams also occur. Recent particles are darkly pigmented, exhibit original shell structure and show no recrystallization. They are easily distinguished from fossil fragments which have been highly recrystallized and, except for the red algae, have retained no structure.

Porosity

The type and amount of porosity are highly variable and may change considerably in laminae. Porosity in light crusts is usually less than 5% with borings constituting approximtely 90% of the total. However, in crusts where bulbous forms are abundant, fenestral voids occur at the crests. Porosity may be up to 20% in the samples examined. Intercrystalline porosity is responsible for the remaining 10%. In red and brown layers of dark crusts, porosity may be as much as 20-25%. Interparticle and intercrystalline porosity are high, 40-50%, with borings generating the remaining 50-60%. Locally, fracture and channel (commonly fenestral) and/or moldic porosity may constitute up to 20% of the

porosity in these laminae. Owing to the extremely dark colour and dense nature of black laminae, porosity of any kind was difficult to determine. Where it occurs, it is less than 1% and typically intercrystalline in nature, but borings may also contribute. Porosity in the terra rossa that commonly overlies the dark crusts may be as high as 30%. Large channels and borings, as well as pores between glaebules account for this.

Channels, vugs and fractures range widely in size from 0.02 to 65 mm long axis. Intercrystalline/ interparticle porosity varies in size from approximately 5 to 15 μm. Boring and moldic porosity are either large, 0.2 to 2 mm diameter, or small, 4 to 9 μm diameter.

Neomorphic Calcite

Neomorphism has taken place in a number of different settings. Discrete crystals of calcite, 0.05 to 0.15 mm in long axis, float in micritic laminae of some light crusts. Many exhibit distinct rhombic shape, while others have no defined crystal form. Crystal boundaries are commonly fuzzy and merge into the surrounding micrite. It was not possible to determine if the spar was being micritized or if the micrite was being replaced by spar. Crystals commonly coalesce to form patches of irregular size and shape in a lamination. Crystals in these patches vary widely in size and show no preferred orientation. Crystal size varies from 0.01 to 0.2 mm. In many instances, entire laminae have been recrystallized. Recrystallized laminations most commonly form the inner part of crusts. Stringers of calcite spar and microspar commonly occur in the red/brown laminations of dark crusts parallel to lamination boundaries. At irregular intervals along their lengths, stringers may be connected to other stringers by spar or microspar to form a boxwork pattern. Neomorphic calcite is a common constituent of the glaebular material associated with dark crusts. It completely surrounds glaebules and commonly replaces centres of glaebules.

Relationship of Crusts to Host Rock

A zone of alteration, which is 0.5 to 5 mm thick, occurs between the crust and the host rock (Fig. 13A) for both light and dark crusts. Laterally, the thickness of the zone varies widely and locally disappears altogether. This zone is easily distinguished from the host

rock by the intense nature of the dissolution. Primary porsity ranges from 50% to, locally, close to 90%. The porosity has been filled by clear calcite spar and the high percentage of spar gives the zone a lighter colour than the adjacent host rock. Etching is indicated by the well defined rhombs and spar filled rhombs of dolomite that protrude into the cavities (Fig. 13B).

Filaments

Numerous filaments penetrate all types of laminae. Straight or slightly curved rod shaped hyphae occur ubiquitously in both types of crusts. The hyphae also penetrate the host rock directly under the crusts. Filaments range in diameter from 3 to 10 μm, but have an average diameter of 3 μm. Some rods are constant in diameter, while others appear to taper. Branching occurs at 90° at irregular intervals along their lengths. Many rods are colourless and appear to be formed of calcite. Others are strongly pigmented and appear black, while others are only pigmented for part of their length. Filament penetration is dense in the micrites of light crusts and highly variable in all other laminae. On the basis of their size and morphology (Klappa, 1979a), the problems in identification notwithstanding, they are interpreted to be fungi.

Black crusts are formed of densely packed, darkly pigmented filaments. In transmitted light, the centre of the filaments appears black, but the edges of filaments commonly appear dark red. Filaments form branching networks that start from the base of a lamina and radiate outwards. This generates a wavy upper surface. Filaments are approximately 0.5 to 1.0 μm in width and 1.0 to 2.0 μm long. Branches range from 0.2 to 0.7 mm in length (Fig. 14A) and are approximately 0.02 mm in wide. Where the filaments are very densely spaced, a black lamina is formed. Where the filaments are less densely spaced, branching networks in red/brown micrite occur. The density of the filaments determines the overall colour and contiguity of a lamination.

The filaments that form the black laminae occur in light crusts as well as dark crusts. However in light crusts they occur in a different form. Rather than forming branching networks, branching filaments radiate outwards from a common point. These radial forms

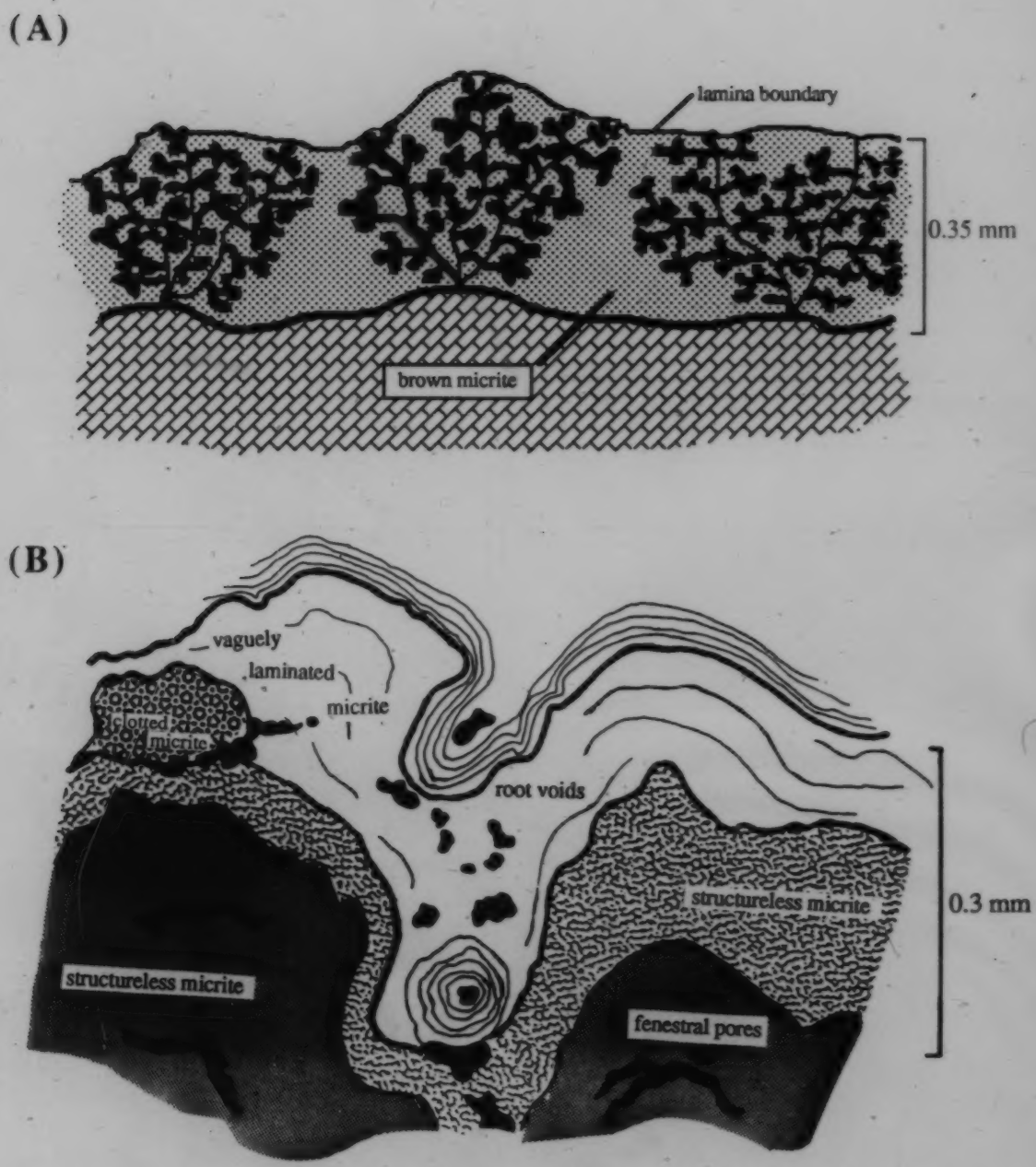

Figure 14. (A) Morphology of branching black filaments. (B) Deformation of laminae around roots. Based on sample 83 GC 305.

occur randomly in the micritic laminae in both light and dark crusts. Black filaments also commonly penetrate the outer surfaces of Recent shell fragments occurring in the other laminae.

Endolithic algae and fungi may be responsible, either directly or indirectly, for the oxidation or reduction of a number of important elements and they are important in the recycling of these elements. The major element cycles that they affect are iron, manganese, silicon, sulfur and carbon (Krumbein, 1983). The fungi have been noted to be the most active of the microflora affecting diagenesis, excluding the bacteria (Krumbein, 1983).

As part of their life processes, microflora may precipitate a number of compounds (Krumbein, 1983). Lockhart (1986) proposed that bacteria are fixing manganese in caymanite. The dark colour of the filaments in both dark and light crusts possibly a result of similar fixing. EDAX analysis identified manganese in the black laminae and precipitation of manganese by the black filaments would account for their opaque nature.

Borings

Borings are numerous and diverse in type and occur in all types of laminae as well as in terra rossas. Diameters of borings tend to fall into two distinct sizes ranges: (1) 0.5 to 9 μm; and (2) 0.06 to 0.70 mm. Lengths of the former range from less than 15 μm to approximately 700μm in length, while lengths of the latter borings are rarely longer than 0.7 mm. Borings of the former group appear to be related to and possibly formed by the straight, colourless and opaque filaments, while the borings of the latter group are a result of roots and rootlets. Actual plant material was removed from samples before preparation of thin sections. Borings may be empty or filled. Borings in light crusts are most commonly filled by calcite, however those in dark crusts may be filled by either calcite or dolomite.

Large borings are commonly an integral part of the laminae of light crusts, with the laminae conforming to one side of the cavity and generally occurring at the base of bulbous growths in the laminae. They also occur penetrating laminae of light and dark crusts and the cements surrounding glaebules. As many as 6 phases of cement commonly line these cavities. In some examples, bands of microcrystalline dolomite alternate with bands of microcrystalline

calcite. They are commonly occluded by calcite spar, but rarely, dolomite may be the final phase occluding the cavity.

Elongate borings 50 μm wide penetrate many glaebules. Borings are restricted in glaebules and do not extend into the sparite that surrounds them. Borings are filled by microcrystalline dolomite.

C. Age of Crusts

Two lines of evidence suggest that the light and dark crusts are being formed by modern surface processes. First, roots and rootlets are found in intimate association with crusts. The upper laminations of crusts commonly grow around (Fig. 14) and coat the roots and rootlets so that the roots become an integral part of the crust. Living roots and/or decaying roots were noted in most crusts examined.

Second, the abundance of Recent shell material incorporated into the crusts implies that the parts of the crusts that contain this material can be no older than Recent in age.

D. Mechanisms of Formation

The crusts appear to be the result of a complex interaction between contructive and destructive processes, though the extent to which they operate depends on the type of crust. Constructive processes include cementation and incorporation of detrital mineral and organic debris, while destructive processes include etching, replacement (aggrading and degrading) and boring.

The boundary between dark crusts and the alteration zone is generally sharp and the initial laminae may be either densely packed black filaments or diffuse black filaments in dark brown micrite. Relic features are not visible in the dark brown micrite, but where the boundary between the host rock and the crust is vague, rare, crystals of dolomite float in the micrite. The filaments are clearly not replacing the host rock; they represent growth on an exposed or lightly soil covered surface. The brown micrite is probably a product of more than one process. Its concomitant occurrence with the black filaments may be a result of

precipitation by the filaments. Calcification and production of micrite by microflora has been documented by many workers (Margolis and Rex, 1971; Bathurst, 1975; Kahle, 1977; Kobluk and Risk, 1977; Kobluk and Kahle, 1978; Klappa, 1979a; Jones and Kahle, 1986). However, the fact that unaltered rhombs of dolomite occur in the micrite implies that, for at least some parts of these crusts, replacement is the process responsible for formation of micrite.

Shell debris and terra rossa glaebules are common constituents of the outer laminae and rarely of the inner and initial laminae of dark crusts. Both constituents occur at the surface and can be found in an unconsolidated state. That they are being actively incorporated into the laminae of the dark crusts is evidence of accretion.

A prominent alteration zone is associated with light crusts, as well as dark crusts. The boundary between the crust and the alteration zone is typically indistinct. Skeletal algal, coral and gastropod structures commonly extend from the host rock, through the alteration zone and into the initial micritic laminae of the crust. Where the crust is primarily alternating bands of micrite, relic skeletal structures commonly extend through several laminations. Relic structures were not observed in bands of calcite spar occurring between laminae of micrite or in any successive laminae overlying bands of spar. Visible relic skeletal structures are evidence of replacement. However, the composition of the initial laminae may vary considerably. Some laminae consist of a mish-mash of patches of dark grey dolomicrite similar to that in the host rock, Recent skeletal particles and patches of micrite in sparry calcite cement. Large, discrete crystals of calcite spar commonly occur in the patches of micrite. The crystals are clear and occur in both rhombic and blocky forms. These crystals also occur less abundantly in successive layers of micrite. Others consist of laminated calcite spar separated by stringers of organic matter or dolomicrite. Both types may grade laterally into patches of neomorphic spar. The patches of neomrphic spar commonly grade into the alteration zone. The presence of detrital material and of cement indicates that in some instances, accretion is an important mechanism in the formation of the light crusts. Replacement of the host rock by micrite as evidenced by relic skeletal structures is the most common situation.

The great variation in texture and composition that occur in the crusts is evidence that a complex interaction of processes is responsible for their formation. The generally well defined boundaries of the dark crusts, marked by the presence of the black filaments appears to be a reflection of crust development on top of a bare or lightly covered surface, while the fuzzy boundaries and micritic laminae of the light crusts may indicate replacement and accretion.

Role of Plants in the Formation of Crusts

Though the evidence is not conclusive, a number of features in the crusts suggest that plants played an integral role in the formation of crusts. Plants, tree roots and their associated microflora, occur in direct contact with both light and dark laminated crusts. Rarely were crusts found in which no plant material, either living or dead was found. A good illustration of this association occurs at Old Man Village caves, where roots penetrating through the roof are surrounded by concentrically laminated crusts (Pls. 3A-3E).

The great number of borings and filaments in both light and dark crusts is another indication of the intimate association of the crusts with plants. Concentric lamination or deformation around borings in light crusts and concentric cementation around large borings in dark crusts indicates that plants are exerting control on the physical formation of the crusts. The upper extent of growth of the black filaments corresponds to the upper surface of a particular lamination. The growth of the filaments therefore also has an affect on the physical form of the crust. It is doubtful that the filaments are acting as binding agents, because many laminae contain no, or few filaments.

E. Discussion

Comparison of Laminated Crusts with Calcretes

Caliches are laminated crusts, which range from nodular and powdery to well indurated, that form in conjunction with pedogenic processes. Calcretes are considered to be

the indurated portions of these crusts (Blank and Tynes, 1965; Multer and Hoffmeister, 1968; Reeves, 1970, James, 1972; Harrison, 1977; Watts, 1980; Arakel, 1981). Calcretes (caliches) are considered to be the *in situ* accumulation of carbonates in a pedogenic profile (James, 1972; Harrison, 1977; Watts, 1980; Netterberg, 1981). Calcretes typically form in the upper few metres of the vadose zone and conform to the present day topographic surface (James, 1972; Harrison, 1977; Watts, 1980). They may also form at the rock-air interface (Harrison, 1977). Calcretes may be laterally extensive or discontinuous and may grade into karst terrains (Harrison, 1977; Esteban and Klappa, 1983).

Petrographically, classic calcretes are characterized by several types and multiple generations of cement, presence of root matter and voids and cement filled fractures. Laminations are distinguished on the basis of preferential colouration of micrites. The laminated crusts of Grand Cayman Island are similar in all these respects.

The most obvious difference between the laminated crusts of Grand Cayman Island and classic calcrete crusts is one of scale. Classic calcrete crusts develop as part of a caliche in a soil profile. Depending on the maturity of the caliche, a single crust several centimetres thick may develop at or near the surface or a zone several metres thick containing many crusts may develop. James (1972) reported up to 18 crusts occurring in profiles from northern Barbados. The crusts lining root borings and cavities occur singly, except in the case of some cavities filled by indurated terra rossa. These cavities commonly contain root boring that are lined by dark crusts.

In addition to the difference in scale, classic calcrete crusts parallel the present day topographic surface (James, 1972; Harrison, 1977; Arakel, 1982). The laminated crusts of Grand Cayman Island that occur in root borings and cavities do not parallel the surface topography. They are site specific.

The most important difference between the laminated crusts found lining root borings and cavities on Grand Cayman Island and classic calcrete crusts is mechanism of formation. Classic calcrete crusts are a result of replacement and *in situ* precipitation of calcium carbonate and other calcium and/or carbonate minerals (Multer and Hoffmeister, 1968;

Reeves, 1970; James, 1972; Harrison, 1977; Watts, 1980; Netterberg, 1981; Arakel, 1982). Where they are forming in unconsolidated soils, lamination is a result of the diagenetic segregation of soil components (Arakel ,1982). While these processes definitely occur in the formation of the crusts on Grand Cayman Island, accretion by incorporation of soil components and cementation are also important and integral processes of formation.

Distinction of Root Borings from Rhizoliths

Klappa (1979) defined rhizoliths as "organosedimentary structures produced by roots." He considered the term synonomous with rhizocretion, pedotubule, root or root-like structure, tubular fossil, Akkyrshi, Dikaka, travertinized root or rhizomorph (Klappa, 1979, p. 614). Rhizolith is a general term that includes all forms produced by the following processes: accumulation and or cementation around, cementation in, or replacement of higher plants by mineral matter (Klappa, 1979). On the basis of these processes, (Klappa, 1979, p. 615) recognized five types of rhizoliths: "...(1) root moulds are tubular voids which mark the positions of now decayed roots; (2) root casts are sediment- and/or cement filled root moulds; (3) root tubules are cemented cylinders around root moulds; (4) Rhizocretions *s. s.* are pedodiagenetic mineral accumulations...around plant roots; and (5) root petrifactions are mineral impregnations or mineral replacements of organic matter which have preserved anatomical features of roots, partly or totally." All of the above processes occur in unconsolidated or poorly indurated sediments and soils. Even where roots occur in the well indurated portions of calcretes, they are considered to be agents responsible for cementation rather than roots boring into the indurated horizon (James, 1972; Harrison, 1977; Semeniuk and Meagher, 1981; Jones, in press). As the roots are boring into well indurated substrates on Grand Cayman Island, the laminated crusts that they are forming do not fit into the category of rhizoliths.

Importance of Root Borings on Grand Cayman Island

Root borings are prominent features of weathering on Grand Cayman Island. Surface boring contributes to the formation of jagged, sponge-like karst forms. Vertical boring produces large conduits (up to 15 cm) that may extend deep into the surface (root borings were observed at depths of 12 m at Pedro Castle Quarry). These conduits are important for diagenesis. They substantially increase the porosity and permeability of the rocks in which they occur. Surface fluids and the organic matter that they contain are thus able to reach greater depths more quickly than if fluid movement was restricted to the primary porosity and permeability of the rock. Preservation of the root generated porosity and permeability will have an equally important effect on future fluid movement and diagensis.

VI. CONCLUSION

The karst environment that has developed on Grand Cayman Island differs from the classic examples of tropical cone and tower karst that have developed on neighboring Cuba and Jamaica. This deviation is a result of the predominantly dolostone lithology, the rapid downward flow of precipitation and the lack of a permanent or ephemeral surface drainage system on Grand Cayman Island.

Despite the deviation of Grand Cayman Island from typical tropical karst, a variety of surface solution features have developed. Small scale solution features include root lapies, solution flutes, rainpits, solution cups, grazing cups, cave popcorn and microfretwork. Larger scale solution forms include grikes, karst wells, irregular pits, pinnacles and caves.

Plants, ranging from boring algae and fungi to tree roots, are extremely important in the weathering process on Grand Cayman Island. The density of boring is such that the surface area, porosity and permeability of the bedrock are all substantially increased. In addition, a number of karst forms are the direct result of plant activity. Root lapies, root grooves microfretwork and lichen stromatolites are surface forms created by plant activity. Root borings and root grooves are deeper forms that create porosity and permeability at depth.

The term phytokarst was originally proposed to describe the action of microscopic algae and fungi boring into the surface of exposed bedrock. 'Phytokarst' is herein proposed to describe a setting in which all plants, macroscopic or microscopic, have a major influence on weathering. Applying this definition to Grand Cayman Island, a variation between two end-members can be seen. These end members are phytokarst of the Ironshore Formation and phytokarst of the Bluff Formation.

Phytokarst on the Ironshore Formation is subdued and there is little or no pinnacle development. Thin, discontinuous soils may be present. Calcrete crusts commonly develop. Phytokarst on the Bluff Formation is exaggerated. Pinnacles are common and well developed. No soil is present.

Two types of laminated crusts that superficially resemble calcrete crusts occur on Grand Cayman Island. They occur in lining root borings, root and soil filled cavities and outlining clasts in terra rossa breccias. These crusts are the result of a complex interaction of constructive and destructive processes. Constructive processes include cementation and accretion by incorporation of soil material into the crusts. Destructive processes include replacement (aggrading and degrading), etching and boring.

PHOTOGRAPHIC PLATES

PLATE 1
SOLUTION FEATURES

(A) Small pinnacle of Bluff dolostone at Cayman Kai showing lacy phytokarst with numerous rainpits. Scale bar = 5 cm.

(B) Popcorn coating cavity wall at East End Quarry. Scale bar = 2 cm.

(C) Chiton in grazing cup on beachrock at Boddentown. Scale bar = 5 cm.

(D) Intricate development of popcorn and microfretwork from Queen's Road. Scale bar = 5 cm.

(E) Solution flutes developed on block of dolostone of Bluff Formation on Queen's Road. Rainpits superimposed on flutes at irregular intervals. Scale bar = 5 cm.

(F) Microfretwork developed on dolostone of the Bluff Formation on Queen's Road. Scale bar = 5 cm.

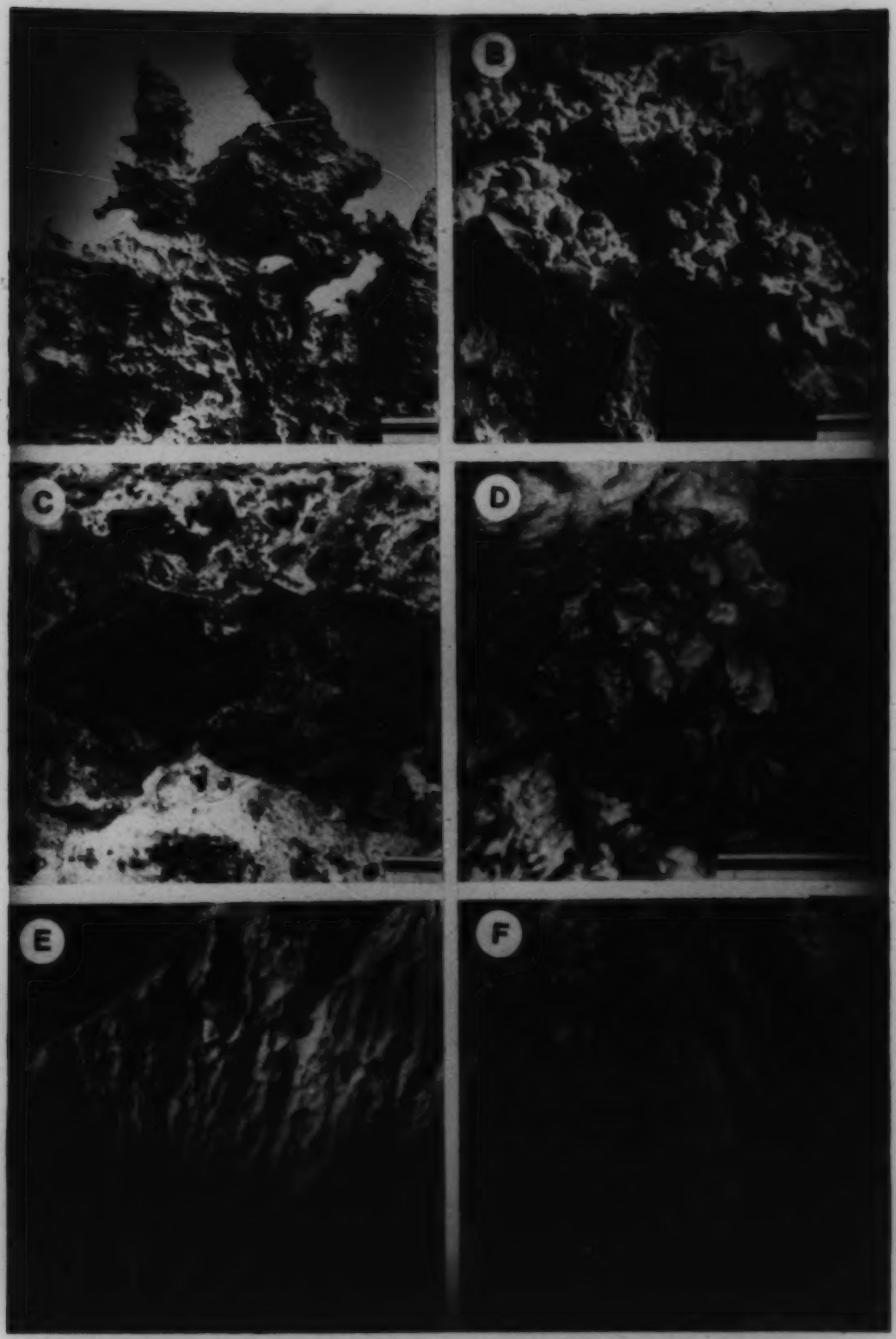
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PLATE 2
SOLUTION FEATURES

(A) Intricate association of roots and root lapies at Cayman Kai. Note range in sizes of roots responsible for formation of lapies. Scale bar = 0.5 m.

(B) Roots of *Ficus sp.* growing directly into dolostone of Bluff Formation on inland path near Tortuga Club. Note absence of soil. Small lapies and rain pits form the pocked surface of the rock enclosing the roots. Scale bar = 0.3 m.

(C) Solution flutes developed on small block at eastern end of island. Small irregular pit (p) in the centre of the block. Scale bar = 0.15 m.

(D) Grikes at Blow Holes. Rainpits and solution cups cover surface of rocks. (Photo courtesy B. Jones) Scale bar = 0.5 m.

(E) Irregular pit developed at eastern end of island near Blowholes. (Photo courtesy B. Jones)

(F) Small pinnacles at Cayman Kai on Bluff Formation. Pinnacle on left shows rectangular shape, while pinnacle on right shows pointed, conical shape. (Photo courtesy B. Jones) Scale bar = 0.5 m.

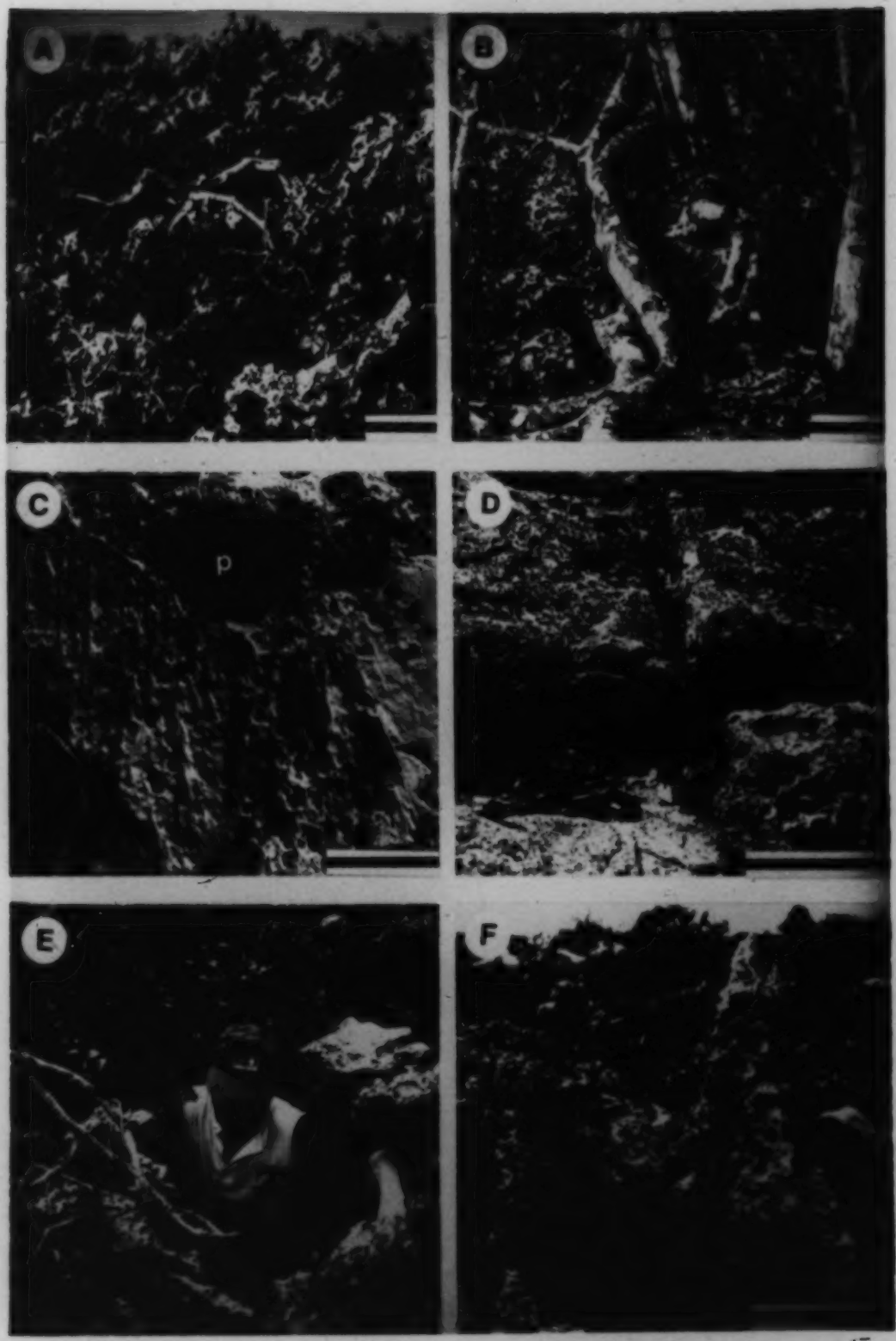
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PLATE 3
ROOTS IN CAVES

(A) Roots extending from roof of cave at Old Man Village. Roots form tangled mass in small accumulations of finely comminuted organic and mineral material. Roots are probably *Ficus sp.* Note pillar (P) in background.

(B) Large roots penetrating roof of cave at Old Man village. Stalactite (S) in foreground. Scale bar = 0.25 m.

(C and D) Roots penetrating roof of cave at Old Man Village showing laminated crusts outlining root borings (arrows). Scale bar (C) = 0.3 m, scale bar (D) = 0.25 m.

(E) Roots growing out of wall in cave at Old Man Village. The walls of the large cavity are defined by a laminated crust (arrow). Compare with the cavities around roots in (B), (C) and (D). Note drapery development (D) under roots. Scale bar = 0.5 m.

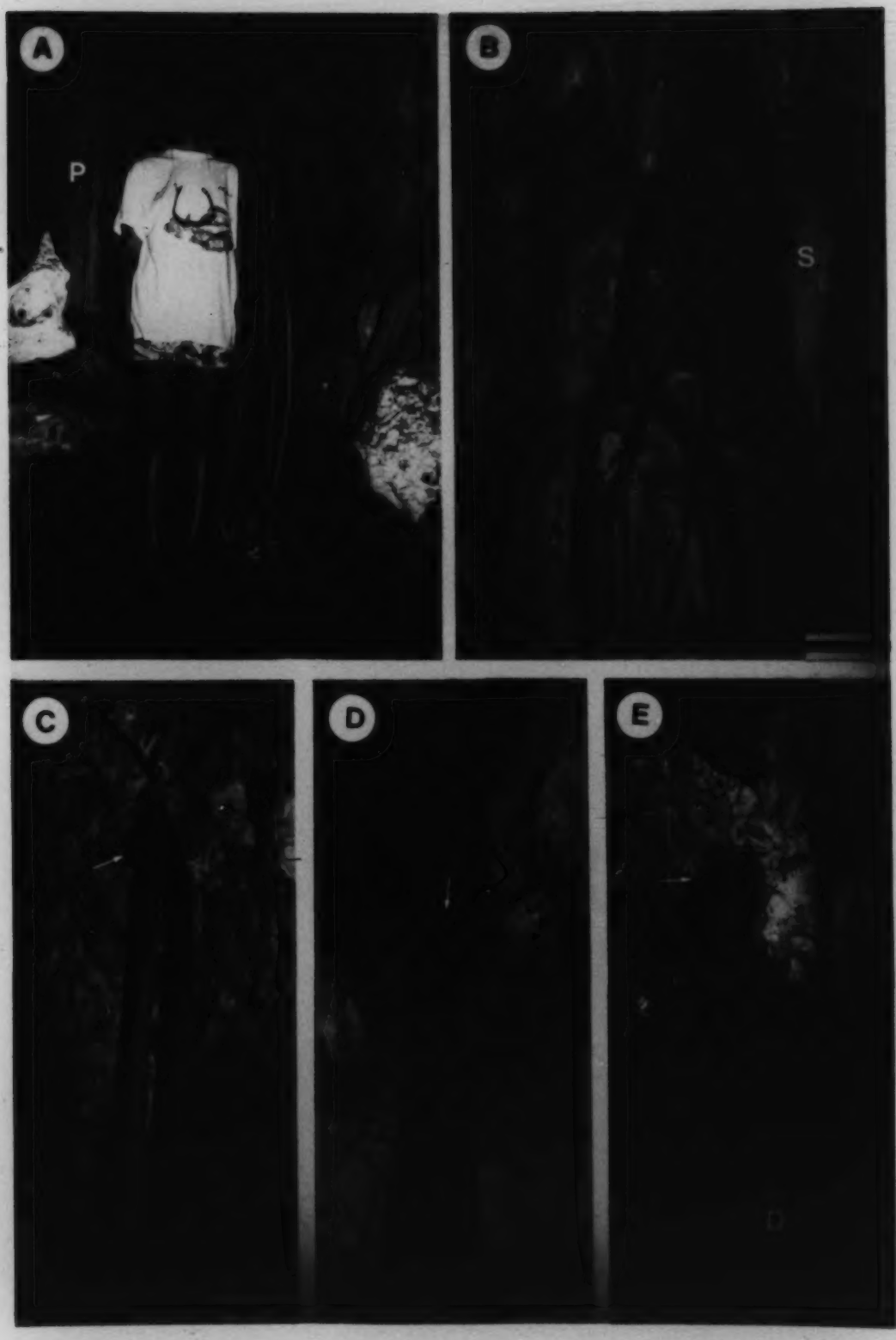
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PLATE 4
SPHEROIDS

(A) SEM photomicrograph showing intensely bored surface of phytokarst. Note different sizes of borings. Scale bar = 10 μm.

(B) SEM photomicrograph showing rootlets penetrating weathered Bluff dolostone. Scale bar = 100 μm.

(C and D)
SEM photomicrograph showing rootlets penetrating both cement and ooids in limestone from Ironshore Formation at Salt Creek. Scale bar (C) = 200 μm, scale bar (D) = 400 μm.

(E) SEM photomicrograph showing densely packed spheroids in root extracted from limestone of Ironshore Formation at Salt Creek. Scale bar = 100 μm.

(F) SEM view of spheroids on broken piece of root from Ironshore Formation at Salt Creek. Scale bar = 50 μm.

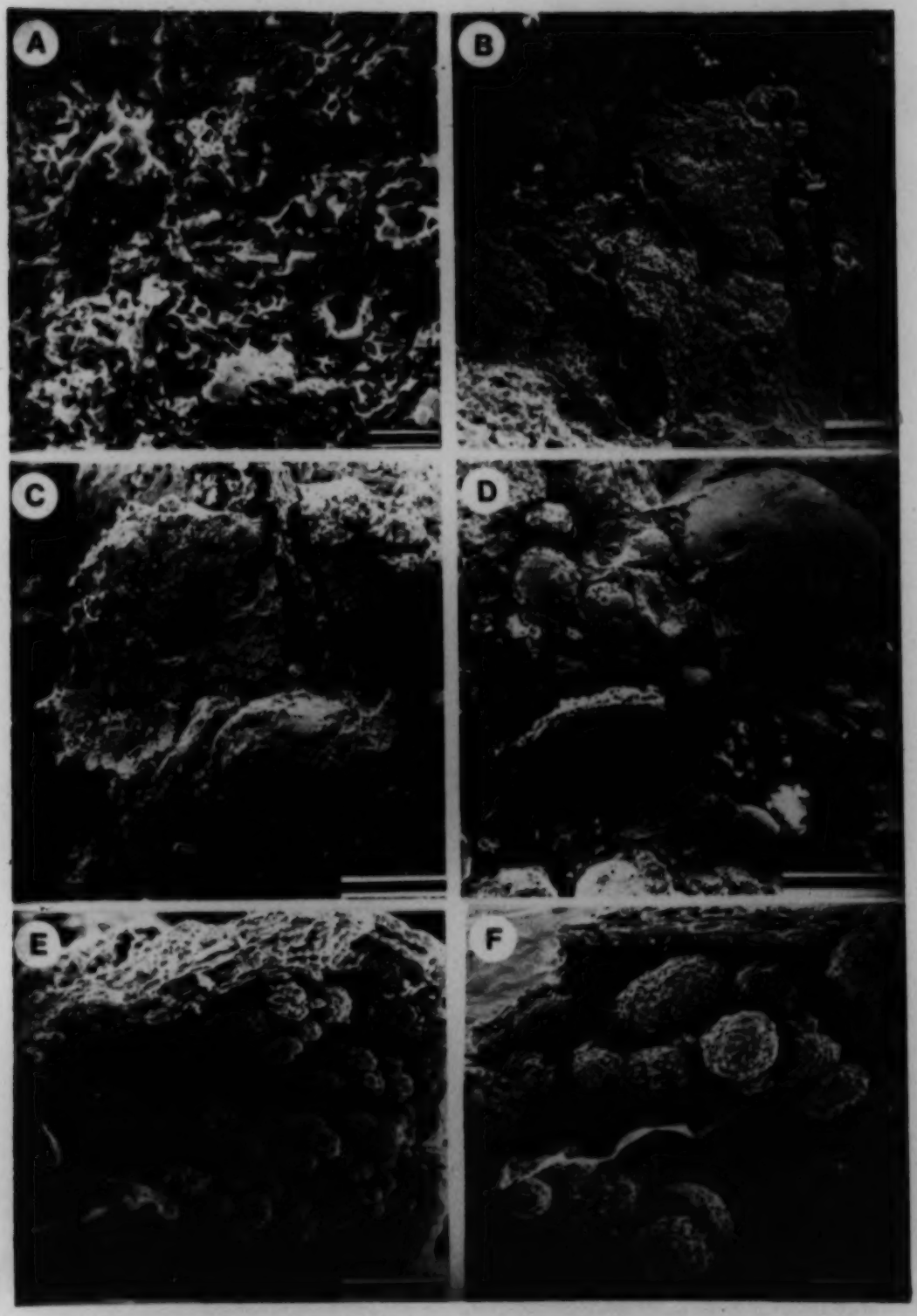
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PLATE 5
SPHEROIDS

(A) SEM photomicrograph of spheroids on inner surface of root. Scale bar = 20 μm.

(B) Higher magnification SEM photomicrograph of spheroid. Note fungal filaments growing over penetrating into surface. Scale bar = 10 μm.

(C) SEM photomicrograph of elliptical examples of spheroids. Note correspondence between shape of spheroids and shape of cells as outlined by cell walls. Scale bar = 150 μm.

(D) Higher magnification SEM photomicrograph of spheroids bound by algal(?) filament. Numerous blebs of halite (arrows) on surface. Scale bar = 20 μm.

(E) Possible growth sites of spheroids. Cell walls have decayed leaving calcium-rich cell-shaped structures. Structures have no internal morphology, but are extremely porous. Porosity possibly because of boring microfilaments. Scale bar = 40 μm.

(F) Calcium rich plates (arrows) sandwiched between epidermal cells of root. Scale bar = 10 μm.

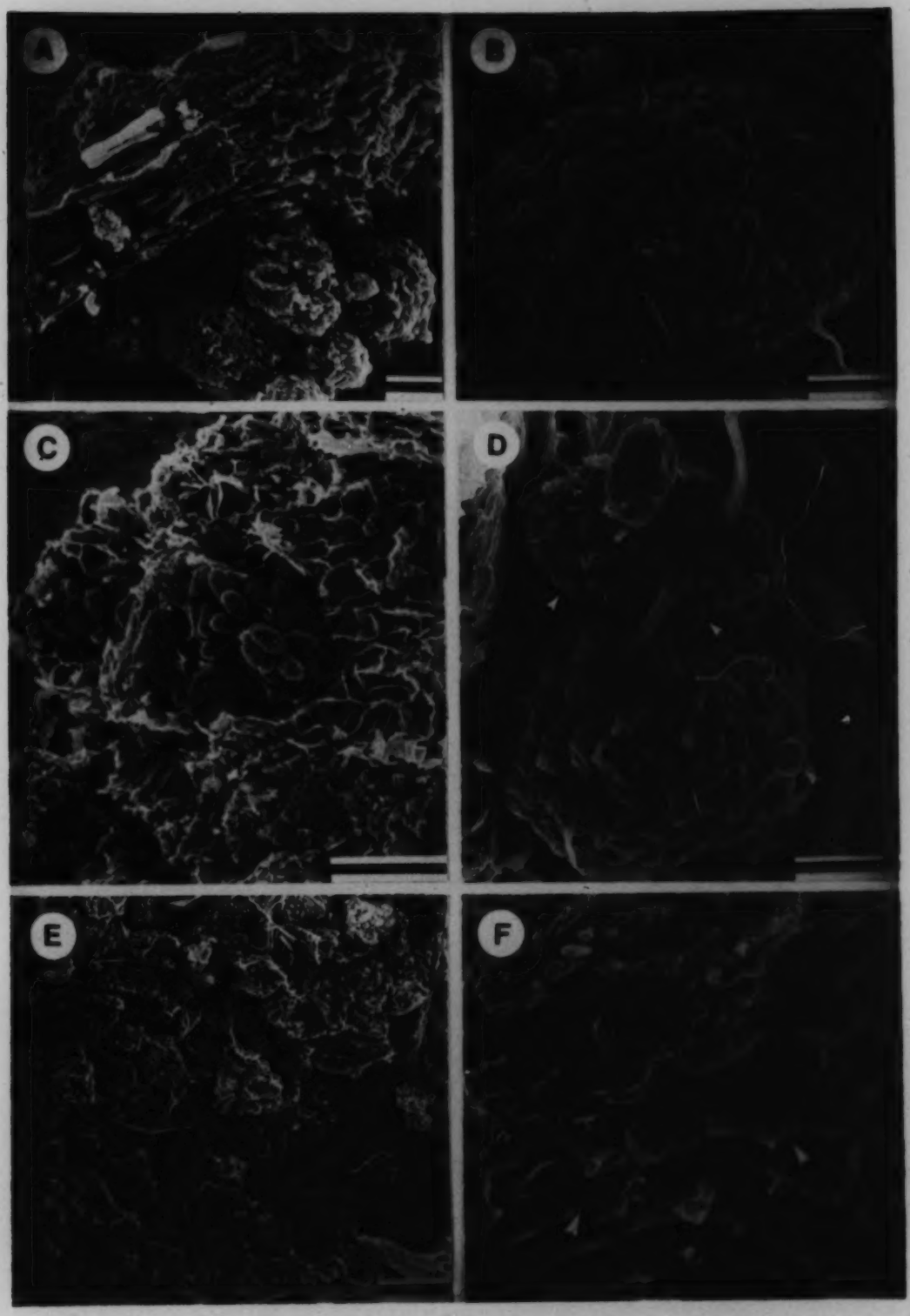
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PLATE 6
LAMINATED CRUSTS

(A) Light crust developed around root boring in Bluff dolostone at High Rock Quarry. Note indistinct boundary between crust and host rock. Scale bar = 2 cm.

(B) Light crust outlining root boring in dolostone at High Rock Quarry. Note diffuse boundary between crust and host rock and wavy, irregular inner surface. Scale bar = 2 cm.

(C) Dark crust outlining cavity in Bluff dolostone at High Rock Quarry. Boundary between crust and host rock is sharp. Inner surface is bulbous and irregular. Scale bar = 2 cm.

(D) Enlarged view of dark crust shown in (C). Scale bar = 2 cm.

(E) Completely filled cavity in Bluff dolostone at High Rock Quarry outlined by dark crust. Cavity filled with indurated terra rossa. Two generations of root penetration are indicated by the dark crust in the centre of the cavity. Scale bar = 2 cm.

(F) Roots (arrows) penetrating terra rossa filled cavity at High Rock Quarry. Scale bar = 2 cm.

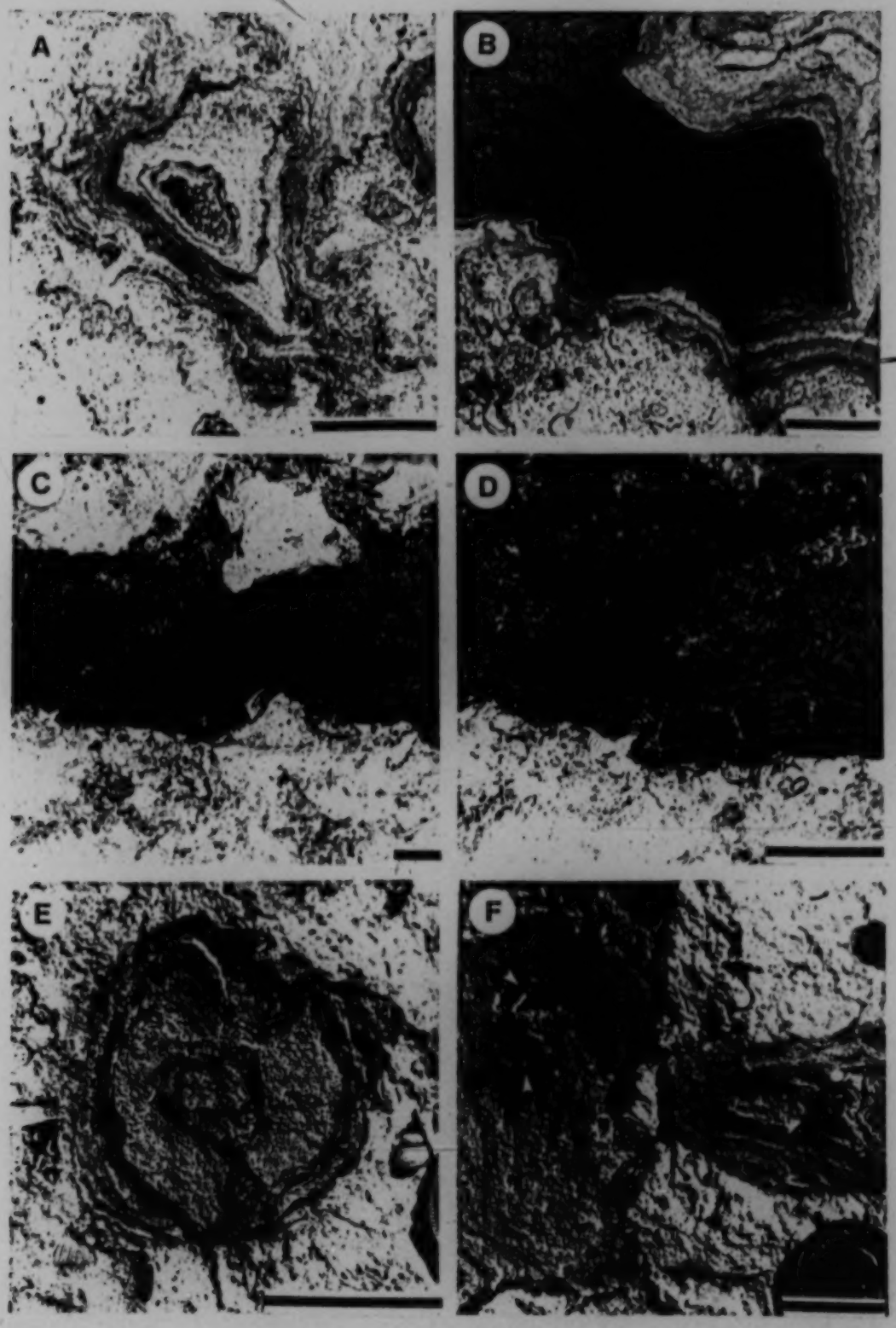
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PLATE 7
GLAEBULES

(A) SEM photomicrograph of "clay ball" in glaebule in terra rossa. EDAX analysis indicates that "clay ball" contains iron. Surrounding material is calcium rich with minor iron. Scale bar = 20 μm.

(B) SEM photomicrograph showing calcite crystals and grains in cavity around root in terra rossa. Note the smaller, hollow dolomite rhomb (d). Scale bar = 20 μm.

(C) SEM photomicrograph of "clay ball" in terra rossa. While texturally similar to the "clay ball" in (A), no iron was detected in EDAX analysis. Scale bar = 10 μm.

(D) SEM photomicrgraph showing glaebules (g) separated by sparry calcite cement (c). Note numerous borings penetrating both glaebules and cement. Scale bar = 100 μm.

(E) SEM photomicrograph of hollow fungal(?) filaments in glaebular material. Scale bar = 4 μm.

(F) SEM photomicrograph of clay particle in terra rossa. Scale bar = 10 μm

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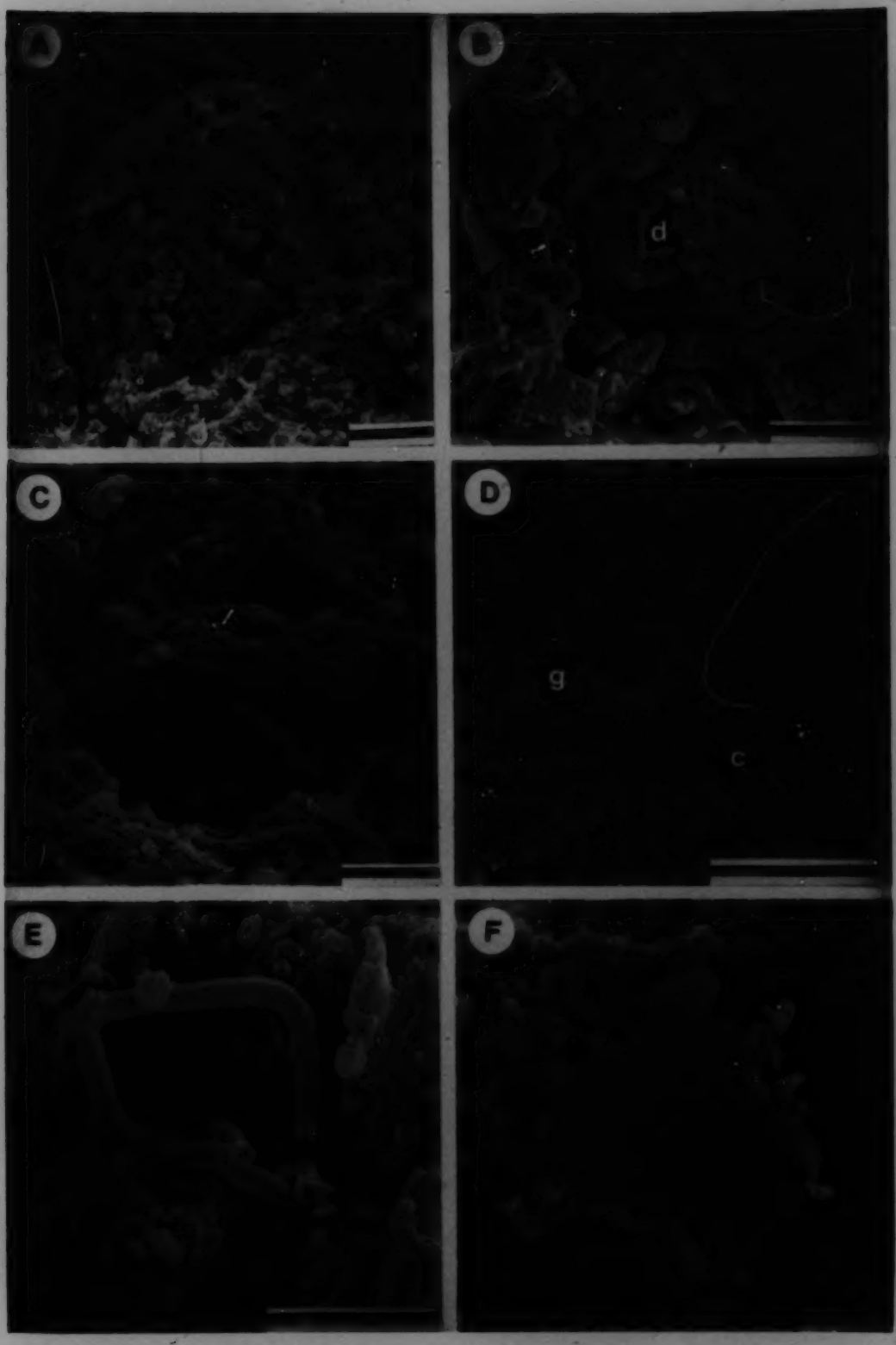
All of the above samples were taken from terra rossa in cavivties in dolostone of the Bluff Formation at High Rock Quarry.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